Part I

NATURAL HAZARDS

"Mitigation is about lowering the risk and reducing the effects of disasters, and this ambitious venture has the potential to reap great rewards. To successfully mitigate against disaster will require the combined talents and concerted efforts of all levels of governments, academia, professional and voluntary organizations, the corporate sector, and all Americans."

William J. Clinton
President of the United States
December 6, 1995

Introduction

Natural phenomena that have the potential to cause fatal and costly damage—such as lightning, windstorms, and floods—are natural hazards. When the damage to life and property becomes real, not just potential, the event is commonly called a natural disaster. Risk assessment involves evaluating the probability and frequency, exposure, and consequences of natural hazard events, where:

- Probability and frequency is a measure of how often a natural hazard event is likely to occur at a particular location;

- Exposure defines the number of people and the number, types, qualities, and monetary values of property subject to the natural hazard event at a location; and

- Consequences are the quantifiable impacts to people and property that may result from an event.

PART I—NATURAL HAZARDS are grouped in the following categories:

SUBPART A: Atmospheric Hazards (tropical cyclones, thunderstorms and lightning, tornados, windstorms, hailstorms, snow avalanches, severe winterstorms, and extreme summer weather)

SUBPART B: Geologic Hazards (landslides, land subsidence, and expansive soils)

SUBPART C: Hydrologic Hazards (floods, storm surges, coastal erosion, and droughts)

SUBPART D: Seismic Hazards (earthquakes and tsunami events)

SUBPART E: Other Natural Hazards (volcanoes and wildfires)

Subpart A

ATMOSPHERIC

HAZARDS

INTRODUCTION

For purposes of this report, phenomena associated with certain weather-generated events are grouped as atmospheric hazards. The individual hazards included are:

Tropical Cyclones

Thunderstorms and Lightning

Tornados

Windstorms

Hailstorms

Snow Avalanches

Severe Winterstorms

Extreme Summer Weather

Each of the atmospheric hazards may have its own natural characteristics, geographic area where it occurs (areal extent), time of year it is most likely to occur, severity, and associated risk. While these characteristics allow identification of each hazard, many atmospheric hazards are interrelated. In most cases, a natural disaster or event involves multiple hazards: severe thunderstorms spawn tornados; wind is a factor in thunderstorms, severe winterstorms, tropical cyclones, and hailstorms; snowfall from a severe winterstorm can prompt avalanches.

Because several atmospheric hazards may occur concurrently, it may be difficult to attribute damage to any one hazard or to assess the risk a particular hazard. On the other hand, mitigation efforts directed at a specific hazard, windstorms for example, often have beneficial effects on related atmospheric hazards.

Although atmospheric hazards are presented separately from geologic, hydrologic, seismic, and other natural hazards, atmospheric hazards may be related to these natural events and often to technological hazards, as well: extreme summer weather contributes to drought; earthquakes cause snow avalanches, landslides, subsidence, and dam failures; and tropical cyclones can exacerbate coastal erosion and flooding.

Photo: Red Cross

TROPICAL CYCLONES

Hurricanes
Tropical Storms
Typhoons

Chapter Summary

Hurricanes, tropical storms, and typhoons, collectively known as tropical cyclones, are among the most devastating naturally occurring hazards in the United States and its territories. Recent events reveal the magnitude of damage that is possible. In 1992, Hurricane Andrew resulted in the highest total damage of any natural disaster in U.S. history, an estimated $25 billion. Tropical Storm Alberto in 1994 caused 30 deaths and $500 million in damage. Puerto Rico and the U.S. Virgin Islands suffered more than $1 billion in damage from Hurricane Hugo in 1989. Hurricane Iniki in 1992 inflicted almost $2 billion in damage to Hawaii. During the past 20 years, more than 75 Federal disaster declarations have involved tropical cyclone activity.

More than 36 million people live in the counties along the Gulf of Mexico and Atlantic Ocean coast, the area of the conterminous United States most susceptible to tropical cyclones. These are also the regions with the highest growth rates and rising property values. The trend of increasing development in coastal zones magnifies the exposure of those areas to catastrophic losses from tropical cyclones. Although the Western States are less prone to landfall by tropical cyclones than the Atlantic and Gulf regions, storms in the eastern North Pacific Ocean have produced damaging rainfalls in California, Nevada, Arizona, and New Mexico. Hawaii and the Pacific territories are at risk from hurricane and typhoon activity year round.

Computer models, improved radar technology, and historical data have enhanced the ability to predict the paths and impacts of tropical cyclones. However, predicting landfall locations with sufficient advance warning remains uncertain. A low-level tropical storm can develop into a hurricane within 6 to 12 hours, yet heavily developed, hurricane-prone areas often require 24 to 36 hours to complete evacuations.

Current mitigation and response efforts rely heavily on public awareness and development of evacuation plans. Adoption and enforcement of strict building codes is one of the more successful long-term mitigation measures for minimizing structural damage. Other efforts include buy-out programs, relocation and/or elevation of structures, improved open-space preservation, and land-use planning in high-risk areas.
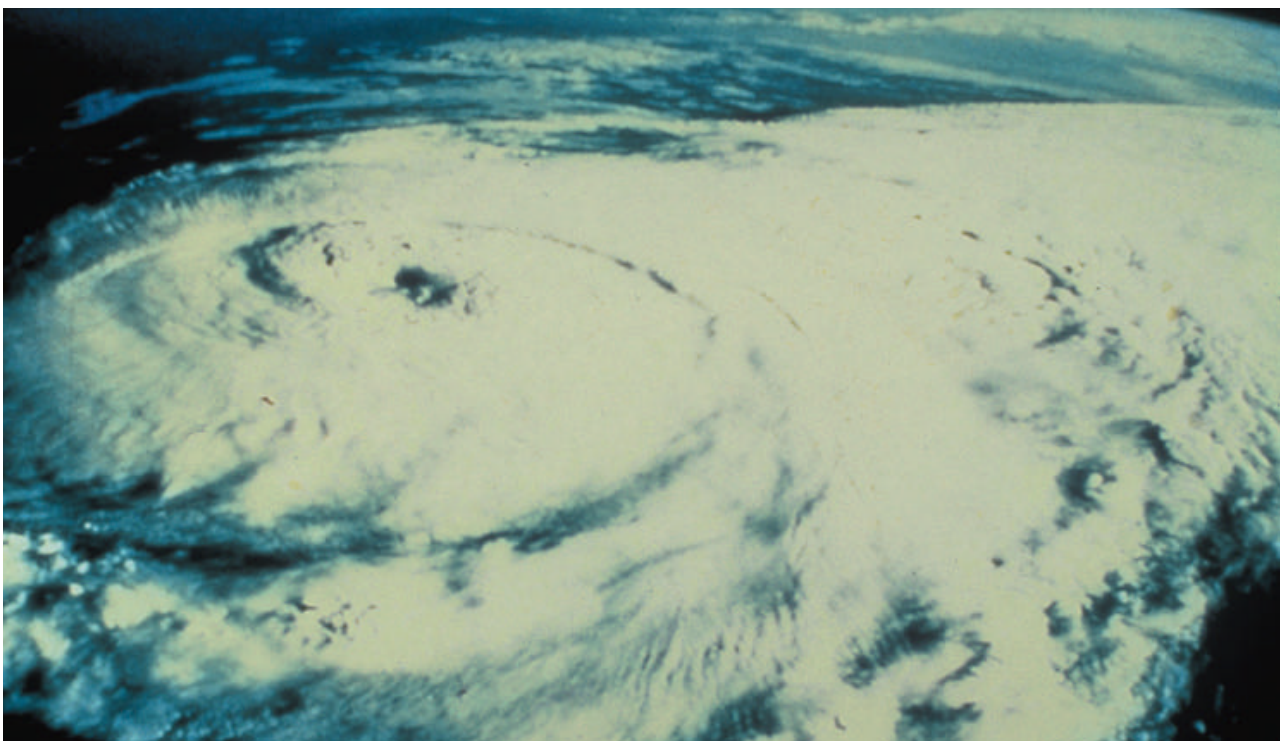

Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

A tropical cyclone is defined as a low pressure area of closed circulation winds that originates over tropical waters. Winds rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

A tropical cyclone begins as a tropical depression with wind speeds below 39 mph (18 m/s). As it intensifies, it may develop into a tropical storm, with further development producing a hurricane or typhoon. As a storm travels over land or colder waters, it eventually weakens. Table 1-1 defines the classification criteria for tropical cyclones based on the stage of development, wind speed, and tropical or subtropical environment.

In the North Atlantic and Central and South Pacific basins east of the International Date Line, tropical cyclones with wind speeds between 39 mph (19 m/s) and 74 mph (33 m/s) are commonly known as tropical storms. When wind speeds exceed 74 mph (33 m/s), they are commonly known as hurricanes. In the western North Pacific basin, tropical cyclones are called typhoons. Typhoons that attain maximum sustained wind speeds of 150 mph (67 m/s) or greater are classified as super typhoons.

The distinguishing feature of tropical cyclones is the eye around which winds rotate. The eye, the storm's core, is an area of low barometric pressure that is generally 10 to 30 nautical miles in diameter. The surrounding storm may be 100 to 500 nautical miles in diameter, with intense windfields in the eastern and northern quadrants. The eye can be seen distinctly in satellite and radar imagery.

The Saffir/Simpson Hurricane Scale is used to classify tropical cyclones by numbered categories (Table 1-2) in the North Atlantic Basin, eastern and central North Pacific Basin, and the South Pacific basin. Hurricanes are classified as Categories 1 through 5 based on central pressure, wind speed, storm surge height, and damage potential.

Tropical cyclones involve both atmospheric and hydrologic characteristics. Those commonly associated with tropical cyclones include severe winds, storm surge flooding, high waves, coastal erosion, extreme rainfall, thunderstorms, lightning, and, in some cases, tornadoes. These individual phenomena are addressed separately in separate chapters in this report.

TABLE 1-1.—*Classification criteria for tropical, subtropical, and extratropical cyclones*

Stage of Development	Criteria
Tropical depression (development)	The formative stages of a tropical cyclone in which the maximum sustained (1-min mean) surface wind speed is <39 mph (<18m/s).
Tropical storm	A warm core tropical cyclone in which the maximum sustained surface wind speed (1-min mean) ranges from 39 to <74 mph (18 to <33m/s).
Hurricane	A warm core tropical cyclone in which the maximum sustained surface wind speed (1-min mean) is at least 74 mph (33 m/s).
Tropical depression (dissipation)	The decaying stages of a tropical cyclone in which the maximum sustained surface wind speed (1-min mean) has dropped below 39 mph (18 m/s).
Extratropical cyclone	Tropical cyclones modified by interaction with nontropical environment. There are no wind speed criteria, and maximum winds may exceed hurricane force.
Subtropical depression	A subtropical cyclone in which the maximum sustained surface wind speed (1-min mean) is below 39 mph (18 m/s).
Subtropical storm	A subtropical cyclone in which the maximum sustained surface wind speed (1-min mean) is at least 39 mph (18 m/s).

Source: *Modified from Neumann and others, 1993*

TABLE 1-2.—*Saffir/Simpson hurricane scale ranges*

Scale Number (Category)	Central Pressure (mbar)	(in)	Wind Speed (mph)	Storm Surge (ft)	Potential Damage
1	≥ 980	≥ 28.94	74 - 95	4 - 5	Minimal
2	965 - 979	28.50 - 28.91	96 - 110	6 - 8	Moderate
3	945 - 964	27.91 - 28.47	111 - 130	9 - 12	Extensive
4	920 - 944	27.17 - 27.88	131 - 155	13 - 18	Extreme
5	< 920	< 27.17	> 155	> 18	Catastrophic

Source: *Hebert and others, 1995*

ATLANTIC REGION. For the coastline from Texas to Maine, tropical cyclones develop over the warm waters of the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean south of latitude 35 degrees. The cooler waters of the North Atlantic Ocean off the central and north-eastern U.S. shorelines usually reduce the strength of storms approaching the shore. The strong steering cur-rent of the Gulf Stream, flowing northeasterly from the coast of Florida past the Outer Banks of North Carolina and up to the maritime areas off Nova Scotia, often directs storms on a track away from the coast. There, storms transition into the extratropical phase and dissi-pate. The primary impact of a tropical cyclone during its rapidly moving extratropical phase is on shipping traffic.

The North Atlantic and northern Pacific Ocean season for hurricanes and typhoons lasts from June through November, when sea and surface temperatures peak. The majority of hurricane activity in the North Atlantic basin occurs during August and September. For the Northern Hemisphere and the North Atlantic basin, Figure 1-1 shows the monthly distribution of land-falling hurricanes striking the U.S. coastline from 1900 to 1994 (Hebert and others, 1995). Table 1-3 lists the most intense hurricanes, categories 4 and 5, to strike the United States between 1900 and 1994.

The peak typhoon season for the Southern Hemisphere and the South Pacific Ocean occurs from October to April. However, the meteorological history of the American Samoa region indicates that major cata-strophic tropical cyclones can strike at any time of year.
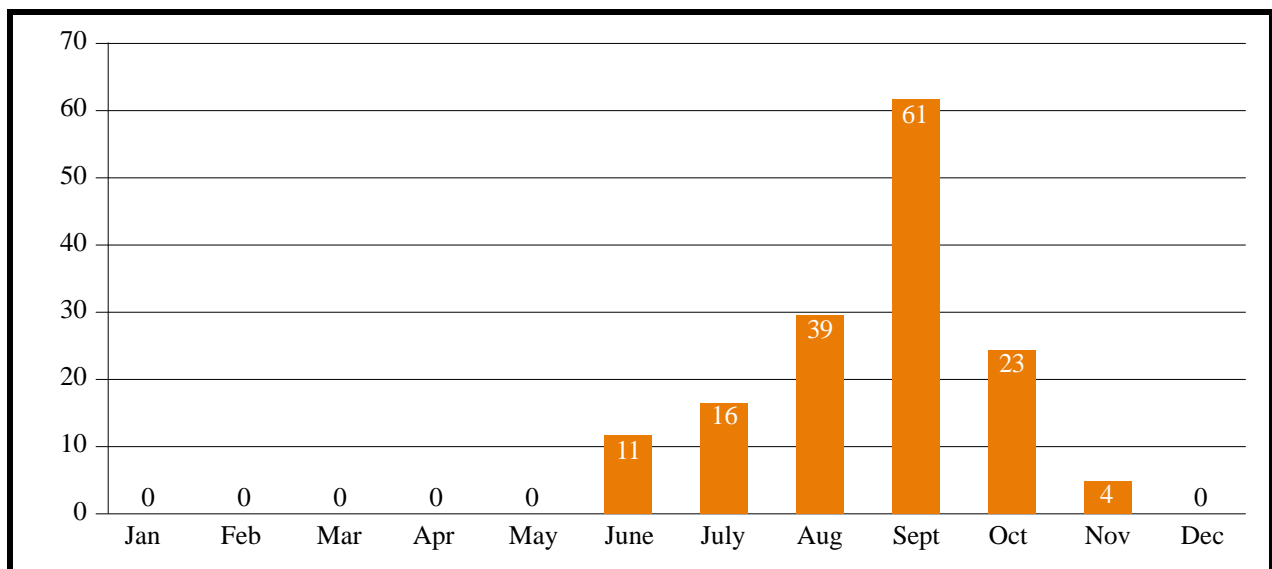

FIGURE 1-1.—Total number of U.S. hurricanes per month: 1900-1994.

Source: *Based on data from Hebert and others 1995*

TABLE 1-3.—*Most intense U.S. hurricanes at time of landfall: 1900 - 1994*

Hurricane	Year	Category	Central Pressure (mbar)	(in)
Florida (Keys)	1935	5	892	26.35
Camille (MS/SE LA/VA)	1969	5	909	26.84
Andrew (SE FL/SE LA)	1992	4	922	27.23
Florida (Keys) /S TX	1919	4	927	27.37
Florida (SE/Lake Okeechobee)	1928	4	929	27.43
Donna (FL/Eastern U.S.)	1960	4	930	27.46
Texas (Galveston)	1900	4	931	27.49
Louisiana (Grand Isle)	1909	4	931	27.49
Louisiana (New Orleans)	1915	4	931	27.49
Carla (N & Central TX)	1961	4	931	27.49
Hugo (SC)	1989	4	934	27.58
Florida (Miami/Pensacola)/MS/AL	1926	4	935	27.61
Hazel (SC/NC)	1954	4	938	27.70
SE FL/SE LA/MS	1947	4	940	27.76
N TX	1932	4	941	27.79

Source: *Hebert and others, 1995*

For the period 1886-1994, an average of five hurricanes a year have occurred in the North Atlantic basin (Hebert and others, 1995). This region is particularly vulnerable because hurricanes occur frequently, the areas are prone to storm surge and coastal riverine flooding, and the population has climbed to an estimated 45 million people. Puerto Rico and the U.S. Virgin Islands are affected by both Atlantic Ocean and Caribbean Sea hurricanes.

PACIFIC REGION.   California, Oregon, and Washington are less prone to landfall by tropical cyclones originating in the eastern North Pacific Ocean. From 1952 through 1971, an average of 6 tropical cyclones occurred each year in this area (Bryant, 1991). Storms tend to move away from the coast, heading toward Hawaii and the open ocean of the central North Pacific. The only effects of tropical cyclones felt in the eastern North Pacific Ocean have been in the form of extreme rainfall in California, Nevada, Arizona, and New Mexico.

Tropical systems approaching the western coastal States tend to lose cyclonic characteristics but retain large areas of convection. As remnants of tropical systems move into the southwestern region, voluminous amounts of rainfall may result. Table 1-4 shows the two-day precipitation totals associated with tropical cyclones affecting the Southwestern States from 1900 to 1984 (Smith, 1986).

Hurricanes impact Hawaii more often than the western States. The island of Kauai has been struck recently by two major storms, Iwa (1982) and Iniki (1992). Although the Islands have experienced hurricanes throughout recorded history, significant coastal flood events had previously been caused by tsunami waves, not hurricanes.

Historical information for hurricanes in the Central Pacific region was compiled by U.S. Army Corps of Engineers (USACE), Pacific Ocean Division, for a 1985 hurricane vulnerability study for Honolulu, HI (USACE, 1985). The report cites the activity of Central Pacific hurricanes based on data from 1832-1979 and updated information for the period of 1980-1983. Before Hurricanes Iwa and Iniki struck, the Kohala Cyclone of August 1871 and the Mokapu Cyclone of August 1938 were considered the most significant tropical cyclones in the Central Pacific.

South Pacific hurricane activity has always been significant in the vicinity of the seven islands of American Samoa. The likelihood of impact from a tropical storm

or hurricane places these islands at risk each year. The risk increases because of the ancillary hazard effects and damage from stream and river flooding, winds in excess of 125 mph (56 m/s), and landslides.

Annual typhoon activity also is very high in the western North Pacific Ocean in the vicinity of Guam and the 14 islands of the Northern Mariana Islands. The lack of a wide continental shelf typical in the North Atlantic basin and the fringing reefs around islands reduce storm surge elevations and wave impacts. Consequently, the severe winds and wind-driven rainfall have much greater effects on island structures and agricultural industries than storm surges.

RISK ASSESSMENT

The various hazard components and risks associated with tropical cyclones come from storm surge, rainfall, and wind. Associated damage includes:

- Storm surge causes coastal flooding, salinization of land and groundwater, water supply contamination, agricultural losses, coastal erosion, loss of life due to drowning, and structural and infrastructure damage;

- Rainfall causes riverine and flash flooding, landslides, loss of life, and damages including structures, infrastructure, and agriculture; and

- Wind impacts utilities and transportation, results in loss of life due to downbursts and tornadoes, creates tremendous amounts of debris, and causes agricultural losses and building damage (Bryant, 1991).

Probability and Frequency

The measure of probability of occurrence for tropical cyclones is generally derived from the coastal flooding caused by storm surge. The probability or return period used to classify the significance of an event is determined as the percent chance of a flood elevation being equaled or exceeded in any given year. The coastal flood elevation caused by a 1-percent-annual-chance tropical cyclone event is commonly referred to as the 100-year frequency flood. The 1-percent-annual-chance flood event is established through detailed analyses of stage-frequency relationships of measured tide level data or analysis and modeling of specific historical tropical cyclone parameters such as direction, minimum central pressure, forward speed, and radius of maximum winds.

TABLE 1-4.—*Two-day precipitation totals, eastern North Pacific tropical cyclones: 1900-1984*

Station	Date	Precipitation (in)
Carlsbad, NM (unofficial)	September 20-21, 1941	17.00
Workman Creek, AZ	September 4-5, 1970	11.40
Mt. Wilson, CA	September 10-11, 1976	10.74
Mt. Wilson, CA	September 25-26, 1939	10.62
Castle Hot Springs, AZ	August 28-29, 1951	10.46
Crown King, AZ	August 28-29, 1951	10.44
Greenville, NM	September 21-22, 1941	8.79
Lake Arrowhead, CA	September 10-11, 1976	8.71
Sunflower, AZ	September 4-5, 1970	8.30
Camp Hi Hill Opids, CA	September 10-11, 1976	8.22
Gladstone, CO	October 4-5, 1911	8.16
Hereford, AZ	September 26-27, 1926	8.15
Newkirk, NM	September 21-22, 1941	8.15
Alamogordo Dam, NM	September 21-22, 1941	8.05
Yates, NM	September 21-22, 1941	8.00

Source: *Smith, 1986*

Detailed hydraulic analyses include the establishment of the relationship of tide levels, wave heights, and synthetic generation of a storm population data base from hydrodynamic models such as TTSURGE and SURGE. The coastal flood elevation for the 1-percent-chance tropical cyclone will be a function of the combined influences of tidal rise and wave setup, height, and run-up along the coastline. A discussion of storm surge elevations and probability of occurrence due to tropical cyclones and other storms is presented in Chapter 13.

The frequency of occurrence of tropical cyclones can be determined by the number of landfall events over a given time period. The frequencies of landfall events are measured from historical data for specific geographic areas of the United States which have experienced direct or indirect hits by hurricanes or typhoons. In an analysis of hurricanes experienced by coastal county populations from Texas to Maine (Hebert and others, 1984), the direct and indirect hurricane landfalls in each county were tabulated. Storms in which the eye passed directly over a county were considered direct hits. Indirect or fringe hits were defined as the areas on either side of the direct landfall zone and were accounted for by assessing the occurrence of hurricane force winds and/or storm surge tides of 4 to 5 ft (1.2 to 1.5 m) in adjacent counties.

In an update of the 1984 study, the assessment was expanded to include the number of direct hits by landfalling hurricanes in coastal States from Texas to Maine from 1900 to 1994 (Hebert and others, 1995). The assessment was modified further using data from the U.S. Department of Commerce to include indirect hits from 1984 to 1994 (Neumann and others, 1993). As shown in Figure 1-2, Florida had the greatest number of direct hits by hurricanes since 1900, with Texas, Louisiana, North Carolina, South Carolina, and Rhode Island ranked in order behind Florida. Florida also has the highest incidence rate of category 3 or greater landfalls.

 Map 1-1 shows the geographic distribution of direct and indirect impacts of landfalling hurricanes affecting coastal counties from Texas to Maine from 1900 to 1994. Map 1-2 depicts the probability of each hurricane category based on events having at least a 5-percent chance of occurring in any given year.

In Hawaii, coastal flood elevations from historic hurricanes have been combined with statistical information on tsunami flood inundation limits and used to establish 1-percent-annual-chance flood elevations and associated wave runup. The combination includes recent significant hurricane events that exhibited tsunami-like wave bore flooding effects.

The most recent information available on Central Pacific hurricanes is the USACE 1985 report. Reliable information about the Hawaiian Islands used was determined to include only the period 1950-1983. For this 34-year period, there was an annual average of two to three tropical cyclones, either tropical storms or hurricanes. The highest number recorded during that period was 10, during the 1982 season. Records show that the month with the highest frequency of occurrence is August, although the devastation of Hurricane Iwa occurred in November, 1982.

USACE found the number of hurricanes peaked during years in which strong El Niño conditions occurred. However, the El Niño, an area of warm surface water in the equatorial region of the eastern Pacific Ocean, is only one of many factors that influence hurricane activity. For 1950 to 1983, USACE identified 20 hurricanes that affected the Hawaiian Islands, but only Hurricane Dot in 1959 made landfall. The next major hurricane to landfall was Iniki in 1992, which also hit Kauai.

According to research in the draft *Survivable Crisis Management Plan for American Samoa* (Department of Public Safety, 1995), the meteorological history of the islands indicates major hurricanes can strike throughout the year. The Joint Typhoon Warning Center (JTWC) reports that from 1981 through 1993, an average of just over 5 tropical cyclones developed each year in the South Pacific basin. However, more than 13 tropical cyclones were recorded in 1992 (JTWC, 1993). The frequency of tropicsl cyclones has not been established in American Samoa.

From 1945 to 1990, 162 tropical cyclones made landfall or came within 180 nautical miles of the island of Guam (JTWC, 1991). In 1994, the JTWC reported that an average of 28 tropical storms developed annually in the western North Pacific from 1960 to 1993. An average of just under 18 of the 28 storms reached typhoon magnitude. Because of the warm tropical waters in the region, typhoons formed during every month of the year during this 33-year period.

In 1993, JTWC reported that the western North Pacific Ocean experienced an above-normal tropical cyclone season, with 30 named storms. In addition, three super typhoons developed, although they did not directly affect the islands. In 1992, five typhoons affected Guam between August 28 and November 24, including Typhoon Omar which passed right over the island.
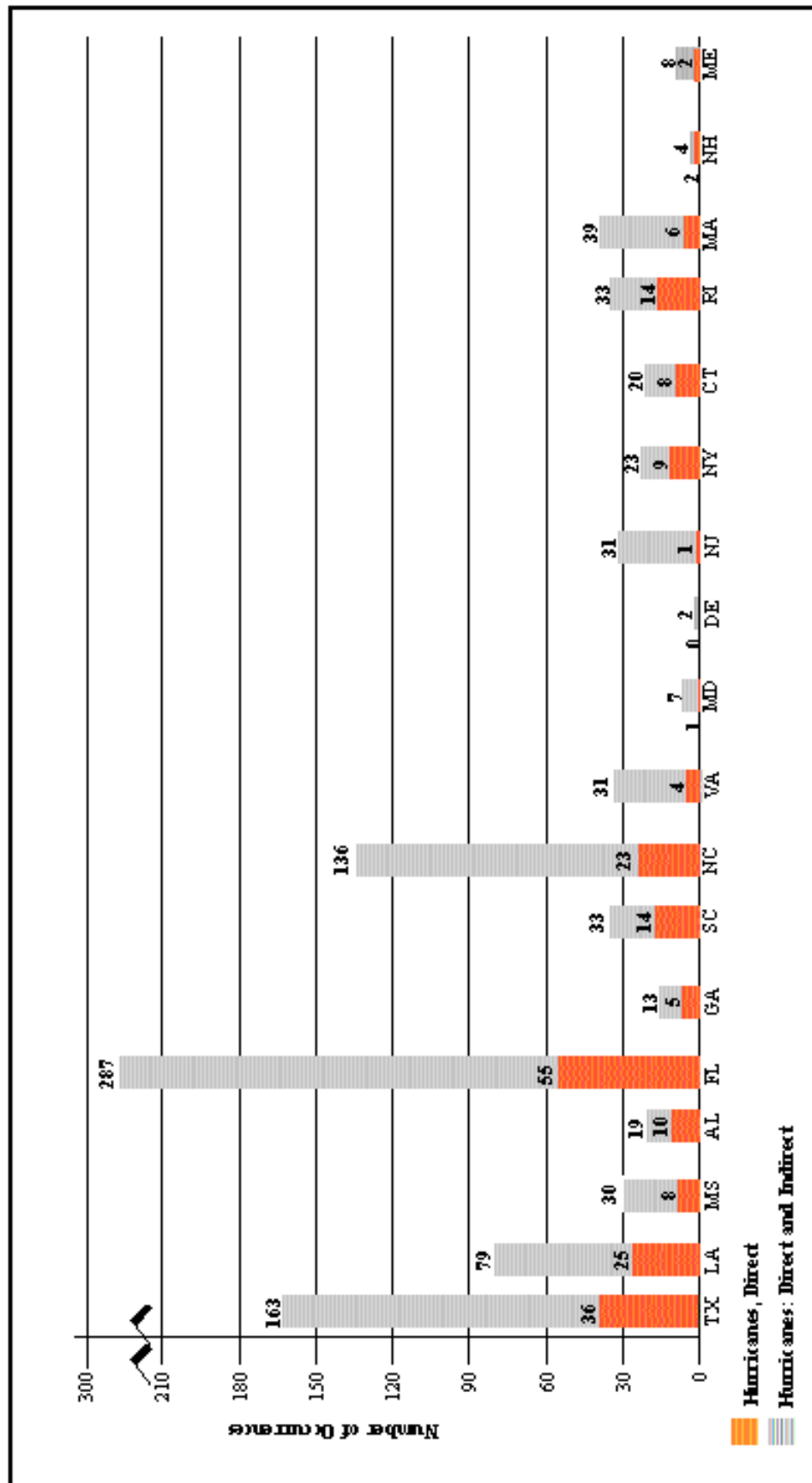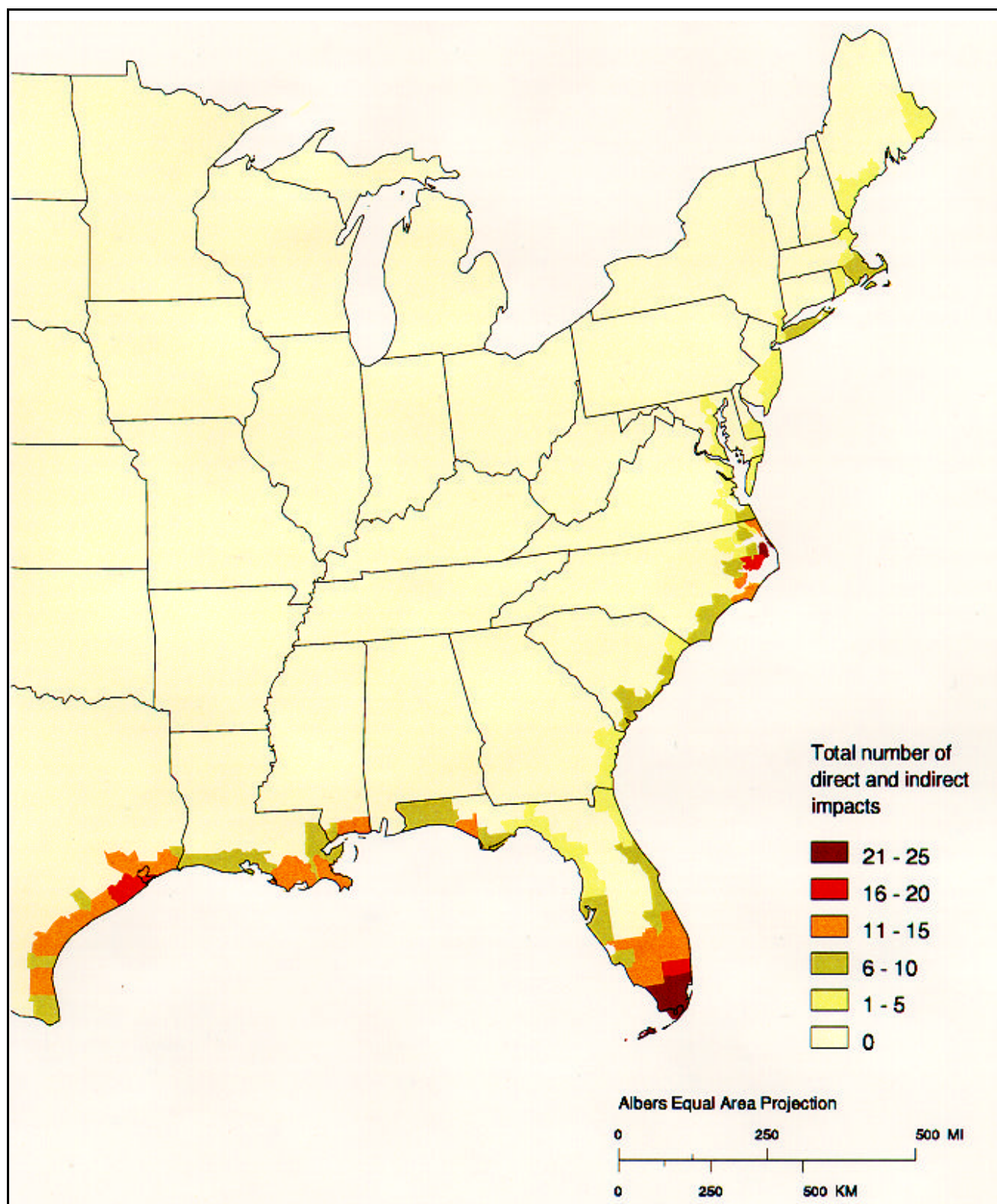
FIGURE 1-2.—U.S. hurricane landfalls (categories 1-5): 1900 - 1994.

Source: *Modified from Hébert and others, 1995*

Total number of direct and indirect impacts

- 21 - 25
- 16 - 20
- 11 - 15
- 6 - 10
- 1 - 5
- 0

Albers Equal Area Projection

| 0 | 250 | 500 MI |
| 0 | 250 | 500 KM |

Map 1-1.   Total number of direct and indirect impacts from landfalling hurricanes for coastal counties
from Texas to Maine: 1900-1994.
Source: *Data from NOAA, National Weather Service, 1994*
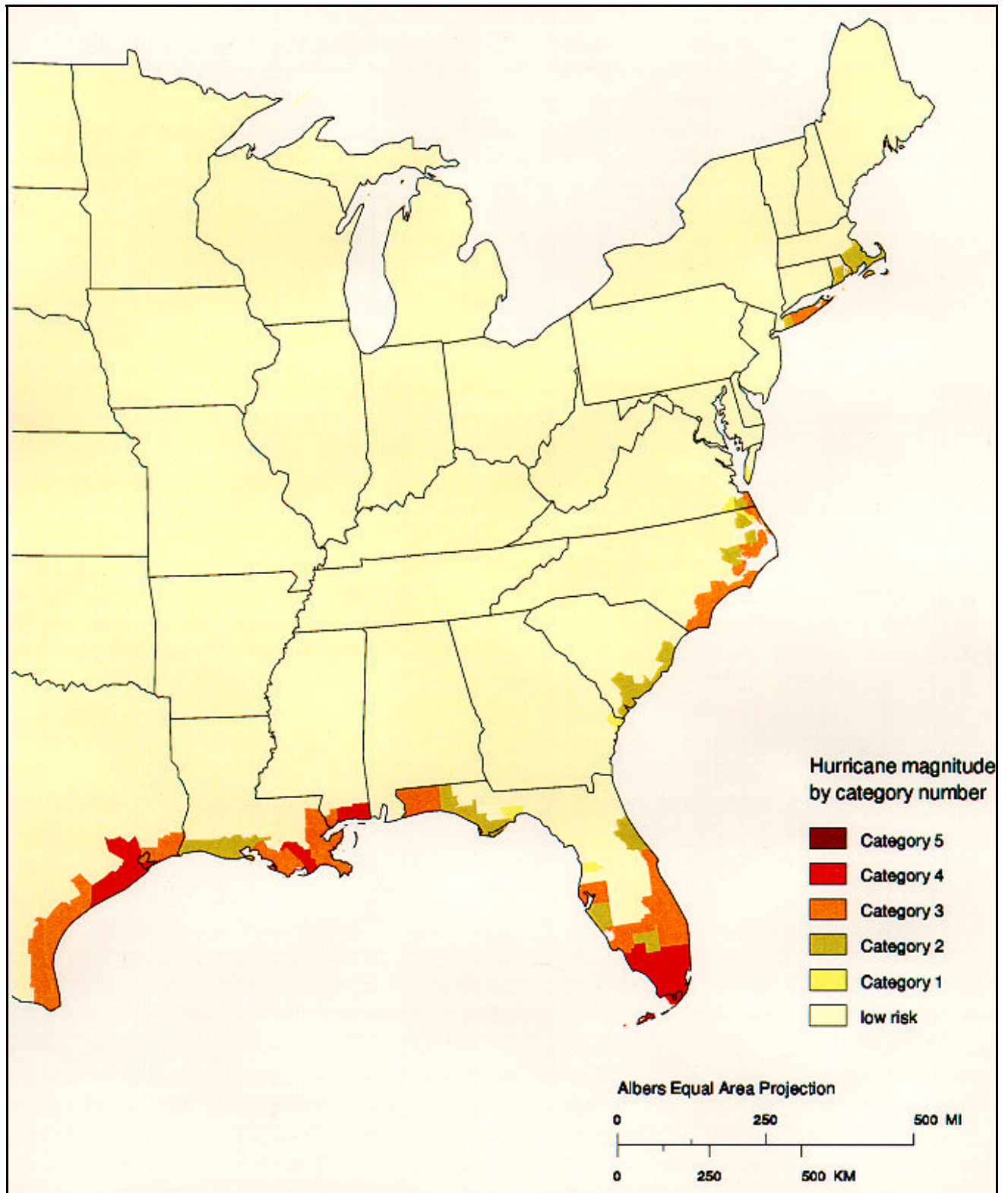
Map 1-2.   Coastal counties from Texas to Maine and the 5% chance associated with the occurrence of landfalling hurricane magnitude (by category) being equaled or exceeded in any given year.
Source: *Data from NOAA, National Weather Service, 1994*

Exposure

Hurricanes present one of the greatest potentials for substantial loss of life, property damage, and economic impact because more than 36 million U.S. residents live in the coastal counties from Texas to Maine that have the greatest exposure to hurricanes.

More than 85 percent of coastal residents have never experienced the effects of a direct-hit hurricane (Hebert and others, 1995). The period from 1970 to 1995 experienced low hurricane activity and few direct hits occurred. Only about one-fifth (12) of the total number of intense hurricanes (Category 3 or higher) since 1900 occurred during the last 25 years. Of those, only Hurricane Agnes in 1972 caused more than 25 deaths.

The highest population growth rates in the United States have been in Gulf and Atlantic coastal counties. These areas have experienced an estimated 15 percent increase in population, more than 5 million people, from 1980 to 1993. For the period from 1988 to 1990, the value of insured residential and commercial property has increased an estimated 65 percent (Insurance Research Council, 1995). Figure 1-3 shows the 1993 value of insured coastal property exposures by State (IRC, 1995).

The nature of the Hawaiian Islands make the entire island chain vulnerable to damage from tropical cyclones and related hazards, but major tropical cyclones appear to be infrequent. On the whole, more significant damage results from tsunami waves, winter coastal storm waves, riverine flooding, and volcanic activity. Development along the coastline is highly valued, and damage from future tropical storms is likely to have significant social and economic consequences.

American Samoa's draft *Survivable Crisis Management Plan* recognizes that devastation caused by hurricanes can affect all aspects of island life. Coastal flood inundation, severe winds, and wind-driven rain impacts residences, transportation, utilities, and agricultural industries. Hurricanes also trigger other natural hazards, such as riverine flooding and landslides.

Consequences

Statistics on the 10 deadliest U.S. hurricanes are presented in Table 1-5. Half of the most costly hurricanes (more than $500 million in damages) occurred in the past 25 years, with Hurricane Andrew in 1992 the most expensive. The 10 costliest U.S. hurricanes of the 20th century are summarized in Table 1-6.

Two recent tropical cyclonic events reveal consequences in densely populated areas: Hurricane Andrew (1992) and Tropical Storm Alberto (1994). Hurricane Andrew resulted in the highest total damage of any natural disaster in U.S. history, estimated at $25 billion for southeastern Florida and southeastern Louisiana. Tropical Storm Alberto was significant because of the extensive inland flooding that occurred as rain fell over the southeastern United States, primarily in Georgia. Although only a tropical storm, Alberto caused 30 deaths and $500 million in property damage. Deaths from Alberto are the highest total recorded for a tropical cyclone since 1975 (Hebert and others, 1995).
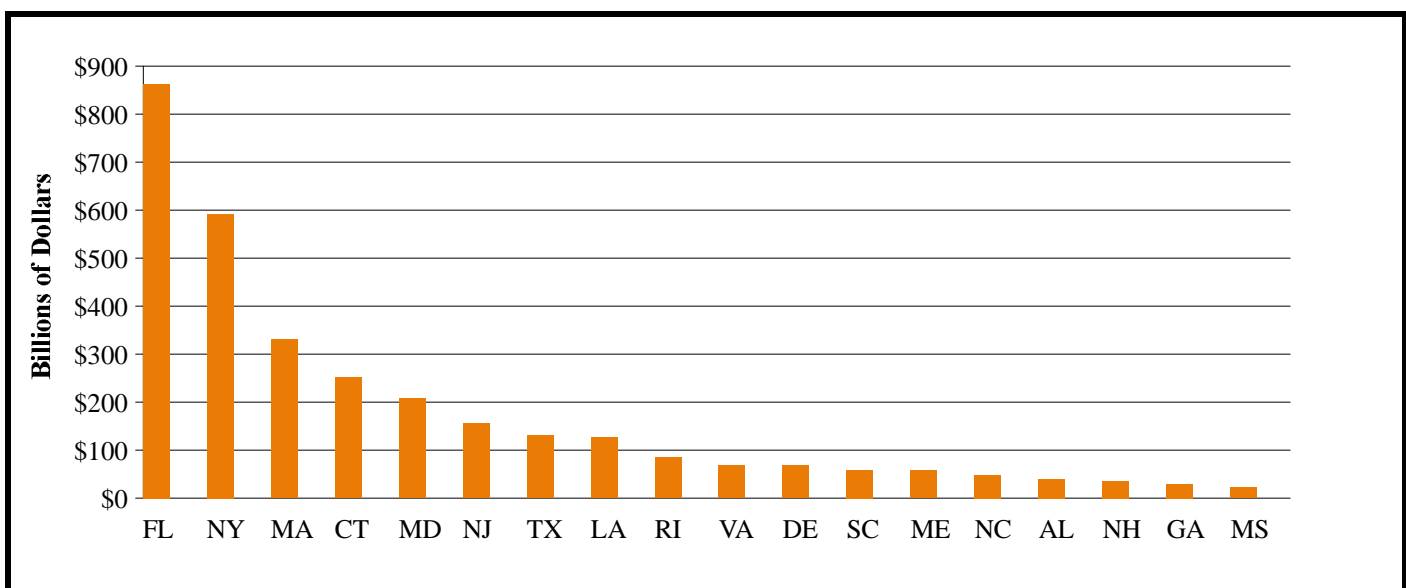

FIGURE 1-3.—Value of insured coastal property exposures by mainland State: 1993.

Source: *Insurance Research Council, 1995, from data provided by Applied Insurance Research.*

TABLE 1-5.—*Deadliest U.S. hurricanes: 1900-1994*

Hurricane	Year	Category	Deaths
Texas (Galveston)	1900	4	8,000+
Florida (SE/Lake Okeechobee)	1928	4	1,836
Florida (Keys/S TX)	1919	4	600[1]
New England	1938	3	600
Florida (Keys)	1935	5	408
Audrey (SW LA/N TX)	1957	4	390
Northeastern U.S.	1944	3	390[2]
Louisiana (Grand Isle)	1909	4	350
Louisiana (New Orleans)	1915	4	275
Texas (Galveston)	1915	4	275

[1] 600-900 estimated deaths, including 500 lost at sea.
[2] Including 344 lost at sea.

Source: *Hebert and others, 1995*

TABLE 1-6.—*Costliest U.S. hurricanes: 1900-1994*

Hurricane	Year	Category	Damage (1990 dollars)
Andrew (SE FL/SE LA)	1992	4	$25,000,000,000
Hugo (SC)	1989	4	7,155,120,000
Betsy (SE FL/SE LA)	1965	3	6,461,303,000
Agnes (FL/NE U.S.)	1972	1	6,418,143,000
Camille (MS/SE LA/VA)	1969	5	5,242,380,000
Diane (NE U.S.)	1955	1	4,199,645,000
New England	1938	3	3,593,853,000
Frederic (AL/MS)	1979	3	3,502,942,000
Alicia (N TX)	1983	3	2,391,854,000
Carol (NE U.S.)	1954	3	2,370,215,000

Source: *Based on Hebert and others, 1995*

In Puerto Rico, about a dozen hurricanes have made landfall in the past 100 years, causing damage to buildings and resulting in significant coastal and riverine flooding. Category 5 hurricanes are expected to hit, on average, every 15 years. In the U.S. Virgin Islands, the primary impacts of hurricanes are severe winds and coastal flooding.

The last major hurricane to affect Puerto Rico and the U.S. Virgin Islands was Hurricane Hugo, a category 4 storm when it passed through the islands on September 17-18, 1989. The majority of the more than $1 billion in damage was a result of severe winds, and nearly 5,000 homes were destroyed.

Previous loss of life and damage from tropical cyclones affecting Puerto Rico include: Tropical Storm Eloise in 1975 with 34 fatalities and over $125 million damage; September 1932 San Ciprian hurricane with 300 fatalities and $30–$50 million damage; the September 1928 San Felipe II hurricane with 300 fatalities and $50–$85 million damage; and the August 1899 San Ciriaco hurricane and associated Arecibo River flood event with 2,184 fatalities and $35 million in direct damage (Palm and Hodgson, 1993).

TABLE 1-7.—*Significant Hawaiian hurricanes of the 20th century*

Name	Date	Damage (1990 dollars)	Deaths
Mokapu Cyclone	Aug. 19, 1938	Unknown	Unknown
Hiki	Aug. 15, 1950	Unknown	Unknown
Nina	Dec. 2, 1957	$900,000	4
Dot	Aug. 6, 1959	$28,000,000	0
Iwa	Nov. 23, 1982	$394,000,000	1
Iniki	Sept. 11, 1992	$1,800,000,000	4

Source: *Based on Hebert and others, 1995*

Tropical cyclone activity in the Pacific Ocean near the Hawaiian Islands is less severe than in the North Atlantic Ocean or western North Pacific Ocean. Nonetheless, as indicated in Table 1-7, many storms have affected the Hawaiian Islands since 1900 (Hebert and others, 1995). In 1992, Hurricane Iniki's landfall on the south shore of Kauai was by far the most destructive hurricane to hit the islands, causing an estimated $1.8 billion in damage from both coastal flooding and severe winds. The cost of damage along the coast was very high due to high property values and the cost of construction.

Damage from recent devastating hurricanes affecting American Samoa includes:

- Hurricane Esau in 1981 caused $1.5 million in damage to public facilities, $3.2 million in agricultural losses and $0.68 million to private structures;

- Hurricane Tusi in 1987 damaged more than 300 structures;

- Hurricane Ofa in 1990, with waves up to 50 ft (15 m) in the open ocean, caused $7.7 million damage to government facilities, $15 million in damage to Ofu Harbor, and total estimated damage of $32 million, including coastal roads and utilities on Tutuila and Ofu; and

- Hurricane Val in 1991 caused one fatality, 200 injuries, and damage in excess of $50 million to structures, utilities, and agricultural crops.

According to the Joint Typhoon Warning Center, Typhoon Omar in the vicinity of Guam in 1992 had sustained winds of up to 121 mph (54 m/s) and inflicted $457 million in damage (JTWC, 1993). Storm surge levels were estimated to be 10 ft (3 m) above normal high tide, and rainfall of 12 to 19 in (30 to 48 cm) fell over 3 days (Coch, 1995). Typhoon Omar's damages included the destruction of 2,158 structures.

From June 1975 to May 1995, more than 76 Federal disaster declarations resulted from coastal storm surge and severe winds associated with tropical storms, hurricanes, and typhoons. Four declarations were issued for Florida. New York, Texas, and American Samoa each had three. Disaster declarations usually include all associated secondary atmospheric and hydrologic hazard impacts of inland flooding and high winds, tornadoes, heavy rain, thunderstorms, lightning, and coastal erosion.

Secondary economic impacts have been noted in recent hurricane disasters in Florida and Georgia, far beyond the immediately apparent damage. Agriculture and tourism in south Florida were disrupted long after Hurricane Andrew's landfall. It is difficult to estimate the magnitude of losses to these industries. Some businesses relocated from the impacted area to relatively safer locations in the central and northern parts of the State. This left many skilled workers either without employment or faced with relocation, increasing the extent of secondary economic losses.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Key research efforts on tropical cyclone activity, characterization, and evolution have been undertaken by the National Oceanic and Atmospheric Administration (NOAA) and its divisions: National Hurricane Center (NHC), Atlantic Meteorological and Oceanographic Laboratory (AMOL), and National Weather Service (NWS). University researchers have conducted extensive work on, and monitoring of, significant storm events.

NOAA has documented the history and tracks of tropical cyclones occurring since 1871. Cyclone prediction based on available climactic data, atmospheric conditions, remote-sensing data collection, and other monitoring programs and computer models has progressed

tremendously since the 1950s. NOAA's ability to predict landfall locations to provide adequate advance warning for evacuation is still maturing. Tropical depressions can develop into hurricanes within 6 to 12 hours, and changes in track may occur quickly. However, some heavily developed hurricane-prone areas require 24 to 36 hours to complete evacuations.

Dr. William Gray, Colorado State University, studies tropical cyclones and accompanying atmospheric and other weather patterns. He has found direct correlations between the level of hurricane activity in the North Atlantic basin and influencing factors, including equatorial upper level wind patterns, El Niño, sea surface temperatures and pressures, and rainfall patterns in the Saheel desert region of Northwest Africa.

Dr. Gray's historical research indicates distinct, 10-year periods of weather and hurricane activity. The number and locations of hurricanes that are category 3 and higher can be attributed to unique combinations of the influencing factors. However, this analysis only serves as a tool to understand a pattern of past weather behavior, it is not a means to make accurate predictions of the severity or location of hurricanes.

The U.S. Army Corps of Engineers and the National Hurricane Center use the Sea Lake Overland Surge from Hurricanes (SLOSH) model to help FEMA and affected States develop specific evacuation plans for urban centers along the Atlantic and Gulf Coast shorelines. SLOSH accounts for different hurricane categories and key combinations of hurricane parameters, including central pressure, forward speed, radius of maximum winds, and angle of approach. The storm surge heights from the models are geographically dependent due to the influence of offshore bathymetry and nearshore topography.

The National Hurricane Center uses other models to predict and forecast the movement and intensity of hurricanes in the North Atlantic basin. The computer models include those prepared by AMOL in Key Biscayne, FL, and a new model developed by the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, NJ. The GFDL model incorporates new mathematical equations of known physical properties of the atmosphere and sea surface and incorporates storm variable parameters for upper level steering currents, windspeed, air and water temperature, and barometric pressure. The GFDL model has improved the forecasting capability of the National Hurricane Center.

For the Pacific Ocean, the Joint Typhoon Warning Center (JTWC) reports that Next Generation Radar (NEXRAD) has been implemented to provide Doppler weather radar capabilities (JTWC, 1993). The JTWC and its U.S. Air Force satellite reconnaissance component are working to improve capabilities in new technology such as the Meteorological Imagery Data Display and Analysis System. The Naval Research Laboratory has begun work on an addition to the Automated Tropical Cyclone Forecast System to improve forecasting capabilities.

MITIGATION APPROACHES

In recent years, loss of life from tropical cyclones has been reduced due to two activities: public awareness campaigns to educate residents about storm preparedness, and development of evacuation plans and actual evacuations of high-risk areas during emergencies.

Regional evacuation planning efforts proved successful in moving residents from the paths of hurricanes in south Florida during Hurricane Andrew (1992) and in South Carolina during Hurricane Hugo (1989). However, continued awareness and public education programs are required to educate new residents who may be unaware of the hurricane threat in high hazard coastal areas.

Mitigation of building damage has been most successful where strict building codes for high-wind influence areas and designated special flood hazard areas have been adopted and enforced by local governments, and complied with by builders. Coastal setback and regulatory programs have helped limit encroachment by some developments near high-risk areas, especially where erosion and wave impacts are anticipated.

During the past 25 years, intense development occurred so rapidly along the many reaches of the coast that building codes and regulatory programs may not have been in place. Without codes, communities did not have adequate mechanism to control the type and nature of structures or construction techniques needed to resist wind and water forces associated with tropical cyclones.

For the most part, buildings constructed prior to adoption of building codes remain more susceptible to damage. Some retrofit projects, for example specially designed shutters and windows for public schools, are expected to reduce future damage. Modification of existing buildings to incorporate hurricane-resistant measures may come about slowly as buildings are substantially improved.

Post-disaster mitigation efforts include buyout programs, relocation, elevation of structures, improved open-space preservation, and land-use planning within

high-risk areas. In many areas of the coast, utility lines and critical transportation routes may have to be relocated to protect against damage resulting from tropical cyclones.

RECOMMENDATIONS

In April 1995, the Insurance Research Council (IRC) and Insurance Institute for Property Loss Reduction (IIPLR) published a report entitled *Coastal Exposure and Community Protection: Hurricane Andrew's Legacy* (IRC, 1995). This report summarized a number of global and specific recommendations from the Southern Building Code Congress International (SBCCI) field team investigations in south Florida following Hurricane Andrew's landfall in 1992. An interdisciplinary group agreed on 15 objectives and strategies in a series of symposia in 1993 that would "facilitate mitigation of natural hazards and foster a cooperative approach among groups that can affect change, including government regulators, code officials and code-making bodies, planners, civil engineers, and insurers" (IRC, 1995). The recommendations for improvements were primarily for the south Florida region, but are applicable to all hurricane-prone areas.

BIBLIOGRAPHY AND REFERENCES

Anders, F., S. Kimball, and R. Dolan. 1989. Map. *Coastal Hazards: National Atlas of the United States.* Map. U.S. Geological Survey.

Byrant, E. 1991. *Natural Disasters.* New York, NY: Cambridge University Press.

Coch, N.K. 1995. *GEOHAZARDS: Natural and Human.* Upper Saddle River, NJ: Prentice Hall.

Culliton, T. J., M.A. Warren, T.R. Goodspeed, D.G. Remer, C.M. Blackwell, and J.J. McDonough, III. 1990. *The Second Report of a Coastal Trends Series: 50 Years of Population Change Along the Nation's Coasts, 1960-2010.* Rockville, MD: National Oceanic and Atmospheric Administration.

Daniels, R.C., V.N. Gornitz, A.J. Mehta, S.C. Lee, and R.M. Cushman. 1992. *Adapting to Sea-Level Rise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical.* Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 3915.

Department of Public Safety, TEMCO. 1995. *Survivable Crisis Management (SCM) Plan for American Samoa* (draft). Pago Pago, American Samoa.

Doehring, F., I.W. Duedall, and J.M. Williams. 1994. *Florida Hurricanes and Tropical Storms 1871—1993: An Historical Survey.* Technical Paper 71, Florida Sea Grant College Program, University of Florida.

Federal Emergency Management Agency, Federal Insurance Administration. 1994. *Mitigation of Flood and Erosion Damage to Residential Buildings in Coastal Areas.* Washington DC.

Federal Emergency Management Agency, Federal Insurance Administration. 1991. *Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program.*

Finkl, C. W., Jr. (ed.). 1994. *Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.* The Coastal Education and Research Foundation, Inc.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." *Reviews of Geophysics.* American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Good, J.W., and S.S. Ridlington. 1992. *Coastal Natural Hazards: Science Engineering and Public Policy.* Oregon Sea Grant. Corvallis, OR: Oregon State University.

Gornitz, V.N., R.C. Daniels, T.W. White and K.R. Birdwell. 1994. "The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast." *Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation.* The Coastal Education and Research Foundation, Inc.

Gornitz, V.M., T.W. White, and R.C. Daniels (ed.). 1994. *A Coastal Hazards Data Base for the U.S. Gulf Coast.* Oak Ridge Laboratory, Environmental Sciences Division, Publication No. 4101.

Gornitz, V.M., and T.W. White. 1992. *A Coastal Hazards Data Base for the U.S. East Coast.* Oak Ridge Laboratory, Environmental Sciences Division, Publication No. 3913.

Hebert, P.J., J.D. Jerrel, and M. Mayfield. 1995. "The Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (And Other Frequently Requested Hurricane Facts)." *Proceedings for 17th Annual National Hurricane Conference, April 11-14, 1995, Atlantic City, New Jersey.*

Hebert, P.J., G. Taylor, and R.A. Case. 1984. *Hurricane Experience Levels of Coastal County Populations—Texas to Maine.* Technical Memorandum NWS NHC 24. Miami, FL: National Hurricane Center.

Insurance Research Council and Insurance Institute for Property Loss Reduction. 1995. *Coastal Exposure and Community Protection: Hurricane Andrew's Legacy.* Wheaton, IL.

Joint Typhoon Warning Center. 1993. *Annual Tropical Cyclone Report.* U.S. Naval Oceanography Command Center, Joint Typhoon Warning Center, Guam, Mariana Islands.

Joint Typhoon Warning Center. 1991. *Tropical Cyclones Affecting Guam (1671-1990).* U.S. Naval Oceanography Command Center, Joint Typhoon Warning Center, Guam, Mariana Islands. NOAA/JTWC Tech Note 91-2.

National Academy of Sciences. 1994. *Natural Disaster Studies Volume Six, Hurricane Hugo: Puerto Rico, the U.S. Virgin Islands, and South Carolina— September 17-22, 1989.* Washington, DC: National Academy of Sciences/National Research Council, Committee on Natural Disasters, Board on Natural Disasters, Commission on Engineering and Technical Systems, Commission on Geosciences, Environment, and Resources.

National Committee on Property Insurance. 1989. *Surviving the Storm: Building Codes, Compliance, and the Mitigation of Hurricane Damage.* Oak Brook, IL: All-Industry Research Advisory Council.

NOAA, National Weather Service. 1993. *Natural Disaster Survey Report: Hurricane Andrew—South Florida and Louisiana—August 23-26, 1992.*

NOAA, National Weather Service. 1993. *Natural Disaster Survey Report: Hurricane Iniki—September 6-13, 1992.*

NOAA, National Weather Service. 1994. *Hurricanes...The Greatest Storms on Earth.*

Neumann, C.J., B.R. Jarvinen, C.J. McAdie, and J.D. Elms. 1993. Supplements (1994) to *Tropical Cyclones of the North Atlantic Ocean—1871 to 1992.* National Oceanographic and Atmospheric Administration, National Climactic Data Center, Ashville, NC, and National Hurricane Center, Coral Gables, FL.

Palm, R.I., and M.E. Hodgson. 1993. *Natural Hazards in Puerto Rico: Attitudes, Experience, and Behavior of Homeowners.* Monograph No. 55. Boulder, CO: Institute of Behavioral Science, University of Colorado.

Smith, W. 1986. *The Effects of Eastern North Pacific Tropical Cyclones on the Southwestern United States.* NOAA Technical Memorandum NWS WR-197. Tucson, AZ: Department of Atmospheric Sciences, University of Arizona.

U.S. Army Corps of Engineers. 1985. *Hurricane Vulnerability Study for Honolulu, Hawaii, and Vicinity, Volume 1—Hazard Analysis.* USACE, Pacific Ocean Division, Floodplain Management Section, Planning Branch.
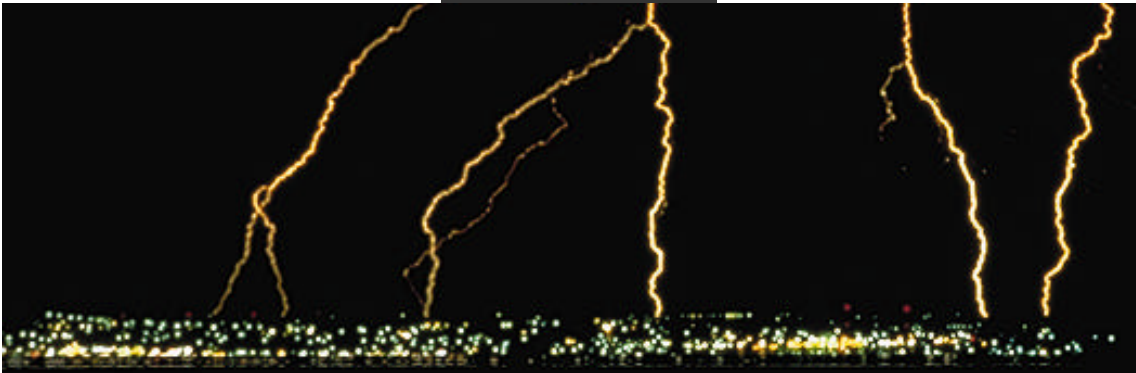
THUNDERSTORMS
AND
LIGHTNING

Chapter Summary

The National Weather Service (NWS) estimates that over 100,000 thunderstorms occur each year on the U.S. mainland. Approximately 10 percent are classified as "severe." Thunderstorms can produce deadly and damaging tornadoes, hailstorms, intense downburst and microburst winds, lightning, and flash floods. Thunderstorms spawn as many as 1,000 tornadoes each year. Since 1975, severe thunderstorms were involved in 327 Federal disaster declarations.

During the past decade, more than 15,000 lightning-induced fires resulted in widespread property damage and the loss of 2 million acres of forest. On average, 89 people are killed by lightning each year, and another 300 are injured. Flashloods from thunderstorms, the number one cause of deaths associated with thunderstorms, claim more than 140 lives in the United States each year. In 1993 alone, thunderstorm winds caused 23 fatalities and $348.7 million in property damage, while lightning caused 43 deaths and damage estimated at $32.5 million.

Florida has the greatest number of thunderstorms and the central region of the State has the highest density of lightning strikes in the mainland United States. The Western States, around the junction of Arizona, Utah, and Nevada, experience the longest duration thunderstorms. The lengthier, less frequent thunderstorms in this region can create as great a hazard as the more frequent, but shorter duration storms in Florida.

Mitigation efforts are directed at the components of thunderstorms: tornadoes, hailstorms, windstorms, lightning, and flash floods. The modernization of the NWS weather monitoring systems and computer models should increase the warning time available to alert local emergency officials and citizens.

Thunderstorms and lightning are underrated killer events experienced in nearly every region of the mainland United States. Thunderstorms do not pose a hazard in the U.S. territories in the Pacific Ocean. Data are not available for Alaska, Hawaii, Puerto Rico, or the U.S. Virgin Islands. Although individual storms have only a relatively small impact area, throughout the world as many as 1,800 thunderstorms can occur at a time.

Photo: Red Cross

HAZARD IDENTIFICATION

Thunderstorm and lightning events are generated by atmospheric imbalance and turbulence due to the combination of conditions:

- Unstable warm air rising rapidly into the atmosphere;

- Sufficient moisture to form clouds and rain; and

- Upward lift of air currents caused by colliding weather fronts (cold and warm), sea breezes, or mountains.

Thunderstorms, sometimes referred to as "thunder events," are recorded and observed as soon as a peal of thunder is heard by an observer at a NWS first-order weather station. A thunder event is composed of lightning and rainfall, and can intensify into a severe thunderstorm with damaging hail, high winds, tornadoes, and flash flooding.

The duration of a thunder event is determined by measuring the time between the first peal of thunder and the last. The last peal of thunder is defined to be that which is followed by a period of at least 15 minutes without an additional peal. A "thunder day" is defined as any day in which at least one thunder peal is heard.

Downburst winds are strong, concentrated, straight-line winds created by falling rain and sinking air that can reach speeds of 125 mph (200 km/h). The combination induces a strong downdraft of wind due to aerodynamic drag forces or evaporation processes (Golden and Snow, 1991). Microburst winds are more concentrated than downbursts, with speeds up to 150 mph (240 km/h). Severe damage can result from the spreading out of downbursts and microbursts, which generally last 5 to 7 minutes. Due to wind shear and detection difficulties, they pose the biggest threat to aircraft departures and landings.

Lightning, which occurs during all thunderstorms, can strike anywhere. Generated by the buildup of charged ions in a thundercloud, the discharge of a lightning bolt interacts with the best conducting object or surface on the ground. The air in the channel of a lightning strike reaches temperatures higher than 50,000ºF. The rapid heating and cooling of the air near the channel causes a shock wave which produces thunder (NOAA, 1994).

The NWS classifies a thunderstorm as severe if its winds reach or exceed 58 mph (km/h), produces a tornado, or drops surface hail at least 0.75 in (1.91 cm) in diameter (Golden and Snow, 1991).

Compared with other atmospheric hazards such as tropical cyclones and winter low pressure systems, individual thunderstorms affect relatively small geographic areas. The average thunderstorm system is approximately 15 mi (24 km) in diameter and typically lasts less than 30 minutes at a single location. However, weather monitoring reports indicate that coherent thunderstorm systems can travel intact for distances in excess of 600 mi (1,000 km).

RISK ASSESSMENT

Dangerous and damaging aspects of a severe thunderstorm, other than tornadoes and hail, are lightning strikes, flash flooding, and the winds associated with downbursts and microbursts. Detailed information is presented separately on tornadoes (Chapter 3), hailstorms (Chapter 5), and flash flooding (Chapter 12).

Probability and Frequency

The probability of a severe thunderstorm occurring in a specific region depends on certain atmospheric and climatic conditions. Duration and frequency can be used as indicators of potential severity. Damage from lightning strikes will likely increase with longer duration and more frequent thunderstorm occurrence. Therefore, the geographic areas with a high density of lightning strikes, measured in units of flashes per square kilometer, are at a greater risk for damage or potential loss of life during a thunder event.

The likelihood of a severe thunderstorm occurring increases as the average duration and number of thunder events increase. Therefore, data collection and combined review of these aspects provide information to assess the areal extent and frequency of the hazard.

NWS collected data for thunder days, number and duration of thunder events, and lightning strike density for the 30-year period from 1948 to 1977. A series of maps was generated showing the annual average thunder event duration (Map 2-1), the annual average number of thunder events (Map 2-2), and the mean annual density of lightning strikes (Map 2-3). Together, these maps indicate the areal extent and frequency of occurrence of thunderstorm and lightning hazards across the mainland United States (Changnon, 1988).

Thunderstorm Frequency.   Maps 2-1 and 2-2 indicate that two areas of the United States are subject to the most damaging thunderstorms, but have different influencing characteristics. South Florida has the greatest number of thunderstorms, with an annual average of 100 to 130, and an average duration of 80 to 100 min-
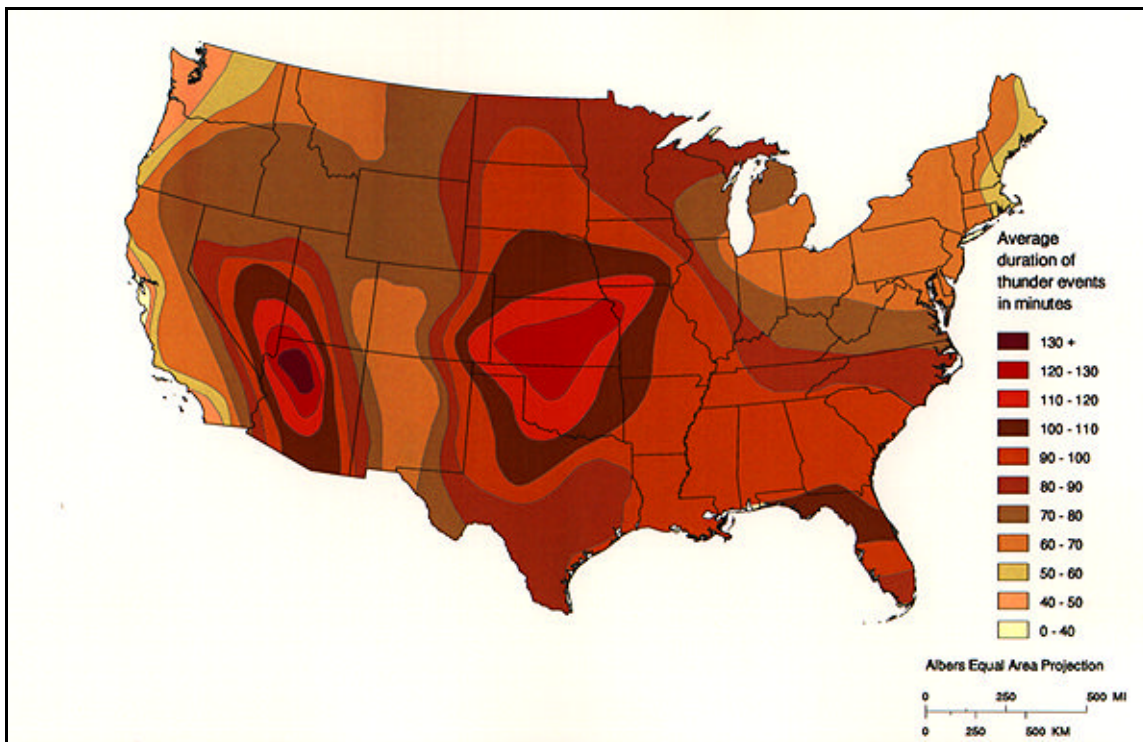
Map 2-1.   Thunderstorm hazard severity based on the annual average duration of thunder events from 1949 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Changnon, 1988.*
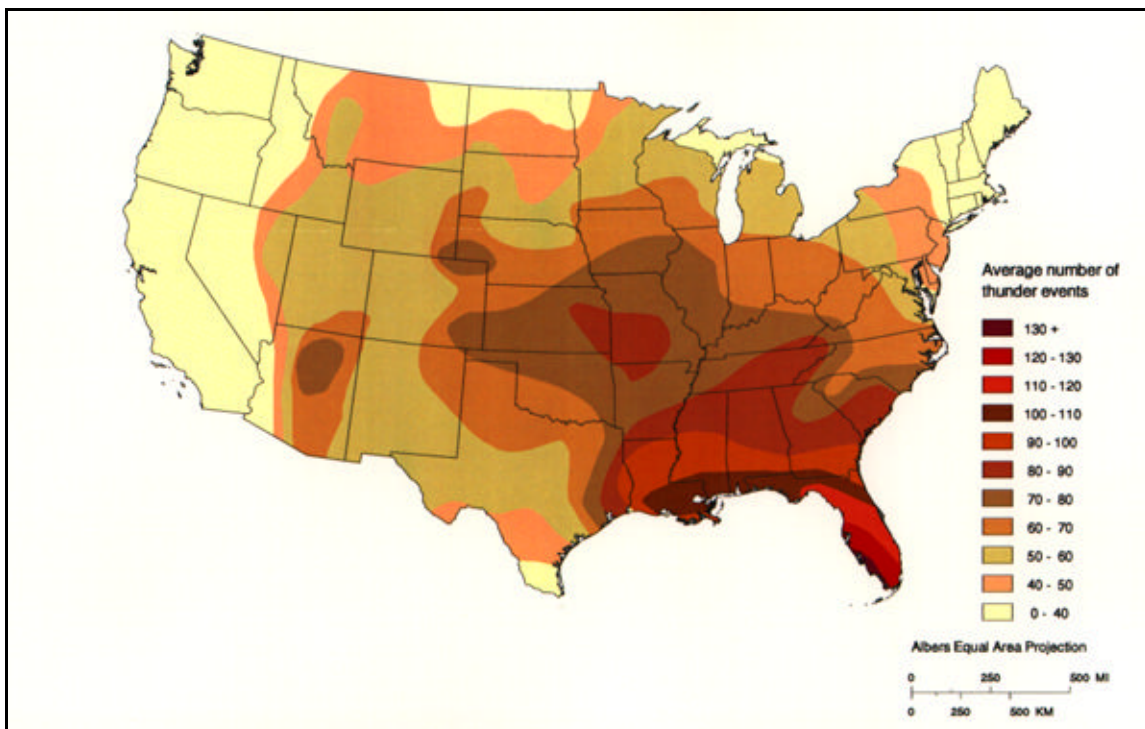
Map 2-2.   Thunderstorm hazard severity based on the annual average number of thunder events from 1948 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Changnon, 1988.*
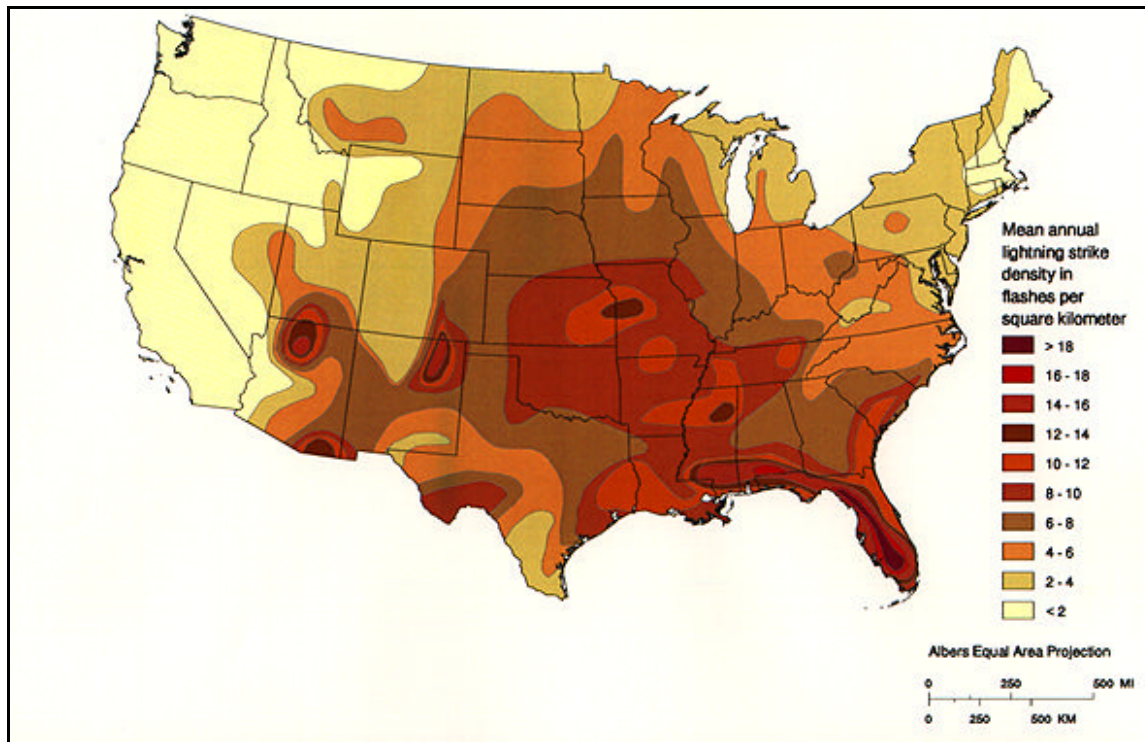
Map 2-3.   Areal extent and severity of lightning hazard based on mean annual lightning strike density: 1948 - 1977. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from MacGorman and others, 1984.*

utes. The area around the junction of Arizona, Utah, and Nevada has an annual average of 30 to 50 thunder events, and the average duration is 110 to 130 minutes. The longer duration, less frequent thunderstorms in this region can create hazards comparable to those experienced in Florida.

The severity of thunderstorm activity in the desert region is influenced by the fact that the annual peak occurrence takes place during a shorter period of time, 3 months during the late summer. In Florida, the season lasts from early summer to late fall, due to the warmer tropical climate and resulting unstable atmospheric conditions favorable for thunderstorm development.

Although severe thunderstorms occur less frequently in the Midwest, the period of activity is not well-defined. Significant activity occurs during different months, but mostly from spring until early winter (Changnon, 1988). The unstable air masses and collision of developing cold and warm fronts during the summer and fall appear to be the cause of activity throughout the Midwestern States.

LIGHTNING FREQUENCY. The lightning hazard component of thunderstorms has been documented by researchers at the NOAA National Climatic Data Center (NCDC), who record the mean annual ground flash density (flashes per square kilometer). Review of these data shows that the central Florida region has over 18 flashes/km², the highest density in the U.S. mainland (Map 2-3). Southern Alabama has the next highest strike density with over 16 flashes/km². Northeastern New Mexico and northern Arizona have isolated high density areas with over 14 flashes/km².

Florida has a higher lightning strike density and more frequent occurrence of thunderstorms, therefore the risk of damaging impacts and loss of life are expected to be greatest. Data were not available for Alaska, Hawaii, Puerto Rico, or the U.S. Virgin Islands, and the Pacific Territories.

EXPOSURE

People and property in virtually the entire United States are exposed to damage, injury, and loss of life from thunderstorms and related hazards such as lightning, severe windstorms, hail, tornadoes, and flash floods. Everywhere they occur, thunderstorms are responsible for significant structural damage to buildings, forest and wildfires, downed power lines and trees, and loss of life. Damage similar to that caused by tornadoes and other cyclonic windstorms can result from severe thunderstorm downbursts and microburst winds. As many as 1,000 tornadoes each year grow out of thunderstorms (Golden and Snow, 1991).

CONSEQUENCES

NOAA reports that thunderstorm winds were responsible for 23 fatalities in 1993, and associated lightning strikes caused 43 deaths (NOAA, 1994). For the same year, damage from thunderstorm winds amounted to $348.7 million, while lightning caused $32.5 million in damage.

According to NOAA, from 1963 to 1993, the average loss of life due to lightning was 89 per year, with an additional 300 persons injured each year. Most lightning-related deaths and injuries occurred when people were outdoors during summer afternoons and evenings. The total number of deaths by State from 1959 to 1993 is shown on Map 2-4.

Significant airplane disasters often are associated with thunderstorms and lightning. Crashes in 1982 in Kenner, LA, and in 1985 in Dallas/Ft. Worth, TX, were attributed to thunderstorm downbursts. In 1963, a plane struck by lightning near Elkton, MD, killed 38 people.

Flash flooding from thunderstorms cause more than 140 fatalities each year and is the primary cause of death from thunderstorm events. Most fatalities occur when people become trapped in automobiles (NOAA, 1994). During the past decade, more than 15,000 lightning-induced fires nationwide resulted in widespread property damage and the loss of 2 million acres of forest.

Severe thunderstorms were involved in 327 Federal disaster declarations from 1975 to 1995. Tornadoes spawned from severe thunderstorms accounted for 106, while several declarations cited thunderstorms and associated phenomena: rain (26), high winds (22), and flash flooding (17).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Thunderstorm wind speeds were included in research conducted by Twisdale and Vickery (1993). The 100-year return period thunderstorm wind speeds were predicted for nine locations in the Central and Southern
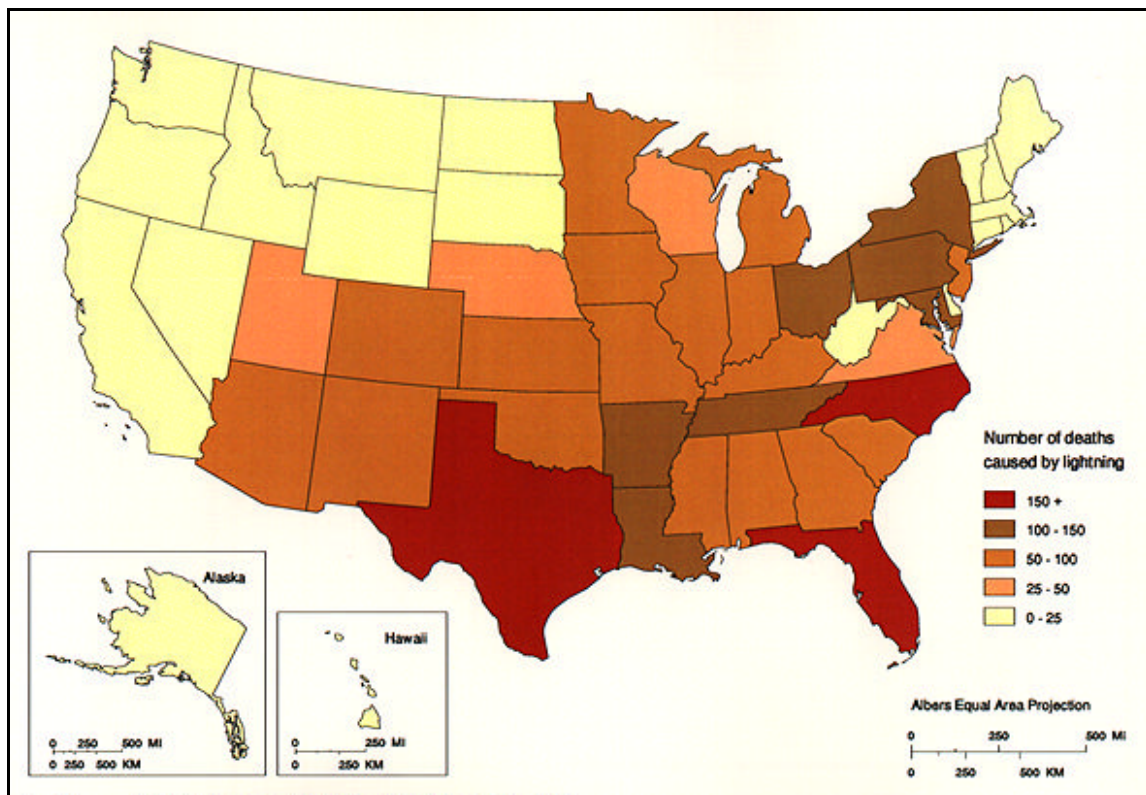
Map 2-4.   Total deaths caused by lightning: 1959 - 1993.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from U.S. Department of Commerce, NOAA, 1993.*

United States, based on daily peak gust data for each site obtained from the National Climatic Data Center in Asheville, NC. The 100-year return periods for highest wind speeds were derived from stochastic models, which predict thunderstorm wind velocities of 66 to 84 mph (106 km/h to 135 km/h) in the Central United States. Each station analyzed showed the highest wind speed on record to be associated with a thunderstorm event.

The National Weather Service has undertaken modernization of weather observation through implementation of NEXRAD systems. The various climatology monitoring programs that allow forecasting of thunderstorms are fairly well-established in each weather-related agency. The forecast centers have been integrated into warning systems for their respective areas. In conjunction with existing Doppler radar weather stations, NEXRAD will improve forecaster capability to predict the development of, and to detect, severe thunderstorms and associated strong winds, hail, lightning, and tornadoes.

MITIGATION APPROACHES

There are no clearly defined mitigation approaches designed specifically for thunderstorms that are separate from the associated hazard phenomena. Mitigation measures for tornadoes, hailstorms, windstorms, and flash flooding can be expected to achieve a reduction in damage caused by or associated with thunderstorms.

Proven techniques are available to reduce lightning damage by grounding techniques for buildings.

RECOMMENDATIONS

The National Research Council (NRC) report on wind hazards, *Wind and The Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation*, includes recommendations applicable to mitigating damage caused by or associated with thunderstorms and lightning (NRC, 1993).

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. *Natural Disasters*. New York, NY: Cambridge University Press.

Changnon, Jr, S.A. 1988. "Climatology of Thunder Events in the Conterminous U.S., Part I: Temporal Aspects" and "Part II: Spatial Aspects." *Journal of Climate*. Vol. 1, No. 4, pp. 389-405.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." *Reviews of Geophysics.* American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Kitsmiller, D.H., W.E. McGovern, and R.E. Saffle. 1992. *The NEXRAD Severe Weather Potential Algorithm*. NOAA Technical Memorandum, NWS TDL 81. Silver Spring, MD: Techniques Development Laboratory.

MacGorman, D.R., M.W. Maier, and W.D. Rust. 1984. *Lightning Strike Density for the Contiguous United States from Thunderstorm Duration Records*. NOAA, Environmental Research Laboratories, National Severe Storms Laboratory.

National Research Council. 1993. *Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation.* Washington, D.C.: National Academy Press.

NOAA, National Weather Service. 1994. *Thunderstorms and Lightning: The Underrated Killers.* U.S. Department of Commerce, NOAA, NWS.

Twisdale, L.A., and P.J. Vickery. 1993. "Analysis of Thunderstorm Occurrences and Windspeed Statistics." In: *Proceedings of the 7th U.S. National Conference on Wind Engineering*. Los Angeles, CA: University of California.

TORNADOES

Chapter Summary

Approximately 1,000 tornadoes each year are spawned by severe thunderstorms. Although most tornadoes remain aloft, those that touch ground are forces of destruction. Tornadoes have been known to lift and move huge objects, destroy or move whole buildings long distances, and siphon large volumes from bodies of water. Over the past 20 years, 106 Federal disaster declarations included damage associated with tornadoes.

Tornado Alley, portions of Texas, Oklahoma, Arkansas, Missouri, and Kansas, is the most susceptible area of the United States. Texas alone averaged 128 tornadoes and 11 tornado-related deaths a year over the 40-year period ending in 1993.

Tornadoes follow the path of least resistance. People living in valleys, which normally are the most highly developed areas, have the greatest exposure. When a tornado warning is issued, local officials typically notify residents with radio and television announcements and alarm systems. Many tornado-prone areas have public shelters, and residents often have specially constructed shelter areas in their homes.

Other hazards that accompany weather systems that produce tornadoes include rainstorms, windstorms, large hail, and lightning.

Photo: Severe Storm Lab

HAZARD IDENTIFICATION

A tornado is a rapidly rotating vortex or funnel of air extending groundward from a cumulonimbus cloud. Most of the time, vortices remain suspended in the atmosphere (Golden and Snow, 1991). When the lower tip of a vortex touches earth, the tornado becomes a force of destruction. Approximately 1,000 tornadoes are spawned by severe thunderstorms each year.

Tornado damage severity is measured by the Fujita Tornado Scale. The Fujita Scale assigns numerical values based on wind speeds and categorizes tornadoes from 0 to 5. The letter "F" often precedes the numerical value. Scale values above F5 are not used because wind speeds above 318 mph (513 km/h) are unlikely. Table 3-1 shows the Fujita Scale values, wind speeds, descriptions of damage, and average annual number of tornadoes for the period 1953-1989.

Tornadoes are related to larger vortex formations, and therefore often form in convective cells such as thunderstorms or in the right forward quadrant of a hurricane, far from the hurricane eye. The strength and number of tornadoes are not related to the strength of the hurricane that generates them. Often, the weakest hurricanes produce the most tornadoes (Bryant, 1991). In addition to hurricanes, events such as earthquake-induced fires and fires from atomic bombs or wildfires may produce tornadoes.

TABLE 3-1.—*Fujita tornado scale*

Scale Value	Wind Speed* Range and Description of Damage
F0	**40-72 mph (17.8-32.6 m/s):** Light damage. Some damage to chimneys; tree branches broken off; shallow-rooted trees pushed over; sign boards damaged. Average number per year, 1953-1989: 218 (29 percent).
F1	**73-112 mph (32.7-50.3 m/s):** Moderate damage. The lower limit is the beginning of hurricane wind speed. Roof surfaces peeled off; mobile homes pushed off foundations or overturned; moving autos pushed off roads. Average number per year, 1953-1989: 301 (40 percent).
F2	**113-157 mph (50.4-70.3 m/s):** Considerable damage. Roofs torn off from houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated. Average number per year, 1953-1989: 175 (23 percent).
F3	**158-206 mph (70.4-91.9 m/s):** Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off ground and thrown. Average number per year, 1953-1989: 43 (6 percent).
F4	**207-260 mph (92.0-116.6 m/s):** Devastating damage. Well-constructed houses leveled; structures with weak foundations blown off some distance; cars thrown; large missiles generated. Average number per year, 1953-1989: 10 (1 percent).
F5	**261-318 mph (116.7-142.5 m/s):** Incredible damage. Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile-sized missiles fly through the air in excess of 100 yards; trees debarked. Average number per year, 1953-1989: 1 (0.002 percent).
	* Wind speeds in the range are defined by Fujita to be "the fastest 1/4-mile wind."

Sources: *From Golden and Snow, 1991: NOAA, NWS Natural Disaster Survey Report, 1991.*

The path width of a single tornado generally is less than 0.6 mi (l km). The path length of a single tornado can range from a few hundred meters to dozens of kilometers. A tornado typically moves at speeds between 30 and 125 mph (50 and 200 km/h) and can generate internal winds exceeding 300 mph (500 km/h). However, the lifespan of a tornado rarely is longer than 30 minutes.

A tornado event occurs when a single atmospheric condition such as a thunderstorm or hurricane generates more than one tornado. Multiple tornadoes generally are the result of many thunderstorms embedded in one large extratropical cyclone or mesoscale convective complex (Golden and Snow, 1991).

RISK ASSESSMENT

The NWS National Severe Storms Forecast Center in Kansas City, MO, provides information on severe thunderstorms and tornadoes to the general public, news media, emergency managers, and law enforcement personnel. The Center uses the latest Doppler radar, wind profilers, and the networks of automated surface observing systems (ASOS) across the United States to assist in the prediction and identification process for severe thunderstorm and tornado watches and warnings.

A tornado watch is issued for a specific location when thunderstorms capable of producing tornadoes are recognized and arrival is expected in a few hours. A tornado warning is issued when tornadoes are spotted or when Doppler radar identifies a distinctive "hook-shaped" area within a local partition of a thunderstorm line that is likely to form a tornado.

When a tornado watch or warning is issued, local tornado spotters, emergency response organizations, and ham radio operators are placed on alert to assist in identifying and locating possible tornadoes. When a tornado is detected, emergency operations personnel and law enforcement agencies are alerted immediately. Warnings are broadcast to the public on radio, television, and alarm systems. Emergency managers and local law enforcement officials sound sirens to notify those who have not already received the information by television, radio, or visual sighting.

Education about tornado hazards continues to be emphasized for schoolchildren in all grades. Residents in tornado-prone areas such as the Southern and
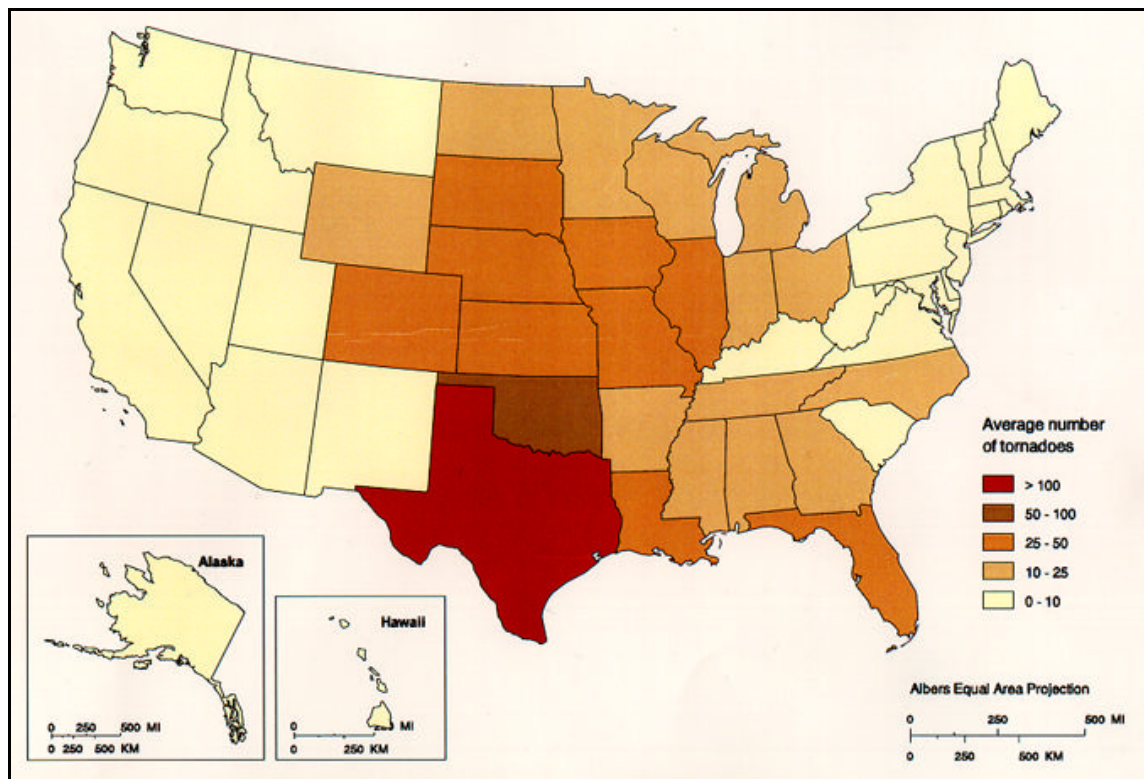
Map 3-1.   Average annual number of tornadoes per State from 1953 - 1993.
             Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
             Source: *Data from National Oceanographic and Atmospheric Administration, 1993.*

Photo: Red Cross

Midwestern States are aware of the dangers and many have underground or specially constructed shelters in their homes. Employees and occupants of unsafe or unprotected facilities are routinely instructed on procedures for safe evacuation.

Probability and Frequency

Map 3-1 shows the average number of tornadoes that occurred each year from 1953 to 1993. Texas experienced the highest average annual number of tornadoes with 128, followed by Oklahoma (52), Kansas (47), Florida (46), and Nebraska (38). Hurricanes Carla (1960), Beulah (1967), and Gilbert (1980) produced 26, 115, and 40 tornadoes, respectively.

The occurrence of F4 and F5 tornadoes may at times be underestimated by as much as a factor of five in some areas of the United States: F5 tornadoes may be listed as F4 tornadoes, F4 tornadoes may be listed as F3 tornadoes, and so on (Twisdale, 1978). This can occur because F3 tornadoes have an F3 intensity for approxi-

mately 35 percent of their duration, and an intensity of less than F3 for the remainder. Similarly, F4 and F5 tornadoes endure at those intensities for 24 percent and 19 percent of their lifespan, respectively (Ramsdell and Andrews, 1986).

There has been considerable research on the relationship between tornado dimensions and tornado intensity: the length, width, and area of the tornado track compared to the probability of being exceeded and strike probability. The arithmetic averages of length, width, area, and strike probability of all tornadoes during the period 1954-1983 have been developed (Ramsdell and Andrews, 1986). These data are available and can been used to assess the risk of tornado hazards.
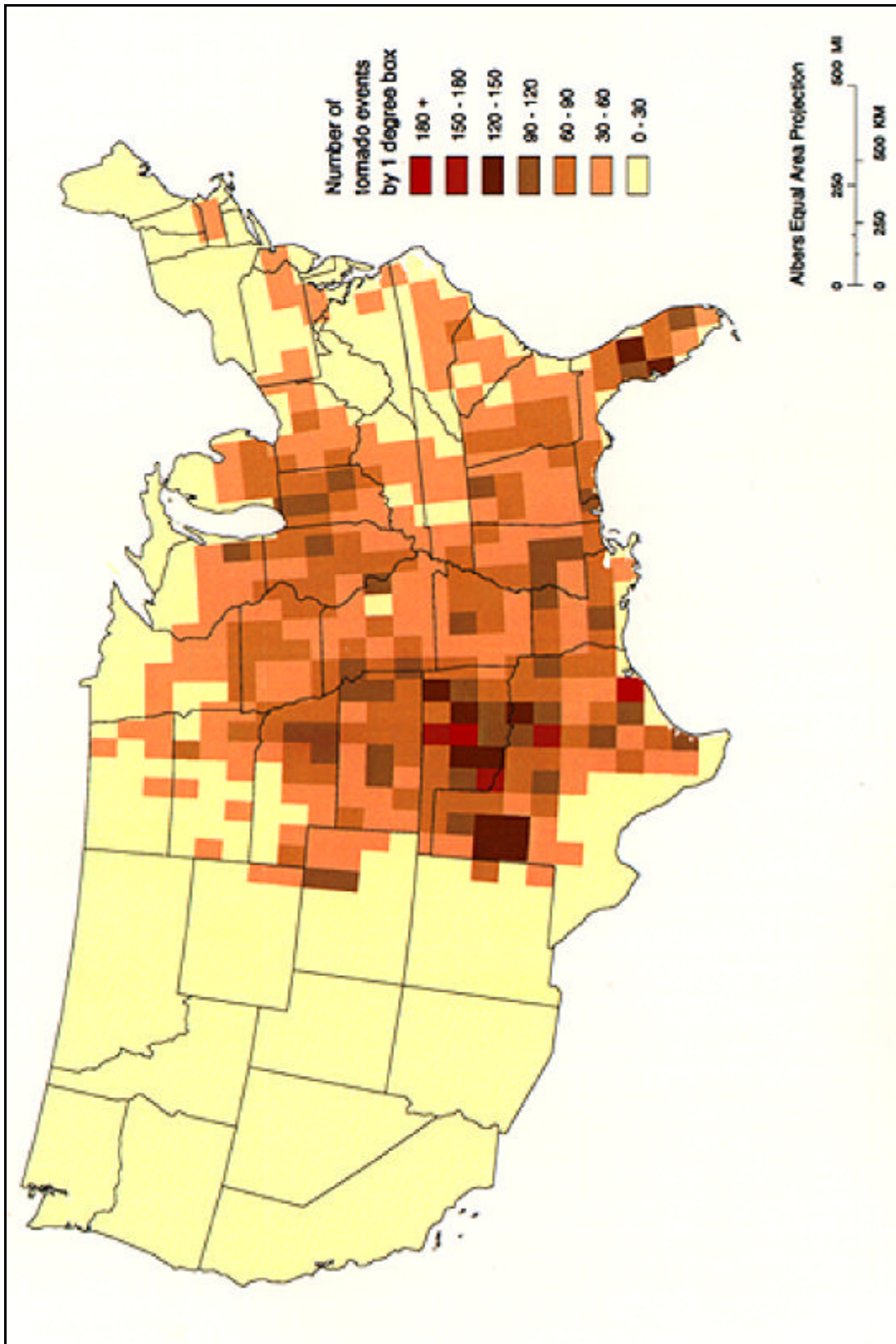
Exposure

An area covering portions of Texas, Oklahoma, Arkansas, Missouri, and Kansas is known as Tornado Alley, where the average annual number of tornadoes is the highest in the United States. Tornadoes occur in this area for several reasons. Cold air from the north collides with warm air from the Gulf of Mexico, creating a temperature differential on the order of 20–30ºC. The flat terrain enhances rapid movement of air, while the high humidity of the Gulf Stream further induces instability in the atmosphere. Most tornadoes in this area occur during the spring (Bryant 1991). People, buildings, and infrastructure located in Tornado Alley have the highest exposure to this hazard.

People living in manufactured or mobile homes are most exposed to damage from tornadoes. Even if anchored, mobile homes do not withstand high wind speeds as well as some permanent, site-built structures.

Ramsdell and Andrews (NOAA, 1986) placed tornado data for the period of 1954–1983 into 1-degree (longitude and latitude) squares on a map of the United States (Map 3-2). Combining this information with data on the estimated population living within each 1-degree area allows assessment of the relative degree of exposure.

Consequences

Tornadoes have been known to lift and move objects weighing more than 300 tons a distance of 30 ft (10 m), toss homes more than 300 ft (100 m) from their foundations, and siphon millions of tons of water from water bodies. Tornadoes generate a tremendous amount of debris, which often becomes airborne shrapnel that causes additional damage. Tornadoes are almost always accompanied by heavy precipitation (Bryant, 1991).

Number of
tornado events
by 1 degree box

180 +
150 - 180
120 - 150
90 - 120
60 - 90
30 - 60
0 - 30

Albers Equal Area Projection

Map 3-2.   Geographic distribution of tornadoes based on total number of tornado events per one degree of latitude and longitude: 1954 -1983.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Ramsdell and Andrews, 1986.*

TABLE 3-2.—*Ten most deadly tornado events: 1870-1979*

Date	Name or Location of Event	Number of Tornadoes	Deaths	Number of States Affected	Estimated Damage *(in millions)*
March 18, 1925	Tri-State	7	740	6	$18
April 5-6, 1936	Tupelo-Gainesville	17	446	5	$18
February 19, 1884	Enigma	60	420	8	$3
March 21-22, 1932	Northern Alabama	33	334	7	$5
April 3-4, 1974	Super	148	315	13	N/A
April 24-25, 1908	Louisiana-Georgia	18	310	5	$1
May 27, 1896	St. Louis, MO	18	306	3	$15
April 11-12, 1965	Palm Sunday	51	256	6	$200
March 21-22, 1952	Dierks, AR	28	204	4	$15
March 23, 1913	Easter Sunday	8	181	3	$4

Source: *J. Galway, Weatherwise Magazine, 1981*

The largest recorded tornado event occurred on April 3–4, 1974, during which 148 tornadoes across 13 States resulted in 315 deaths. Table 3-2 summarizes damage caused by the 10 deadliest tornadoes occurring between 1870 and 1979. Table 3-3 provides similar information for tornado events since 1979.

From 1916 to 1950, 5,204 tornadoes occurred in the United States, resulting in the deaths of 7,961 people, an average of 234 deaths per year (Bryant, 1991). From 1953-1989, tornadoes claimed 3,550 lives, an average of 96 deaths per year. From 1961-1990, the highest number of tornado-related deaths occurred in Mississippi, Indiana, Ohio, Alabama, and Arkansas (Golden and Snow, 1991). According to NWS, 39 tornado-related deaths occurred in 1992, and 33 occurred in 1993.

Map 3-3 shows the average annual number of deaths by State from 1953 to 1993. During that period, Texas had

TABLE 3-3.—*Six most deadly recent tornado events: 1980-1994*

Date	Name or Location of Event	Number of Tornadoes	Deaths	Number of States Affected	Estimated Damage *(in millions)*
May 31, 1985	Pennsylvania-Ohio	41	75	3	$450
March 28, 1984	Carolinas	22	57	2	$200
March 27, 1994	Southeastern U.S.	2	42	2	$107
November 21-23, 1992	Houston to Raleigh and Gulf Coast to Ohio Valley	94	26	13	$291
April 26-27, 1991	Wichita/Andover, KS	54	21	6	$277
October 3, 1992	Tampa Bay Area	3	4	1	$100

Source: *From NOAA, NWS Natural Disaster Survey Reports, 1985-1994.*
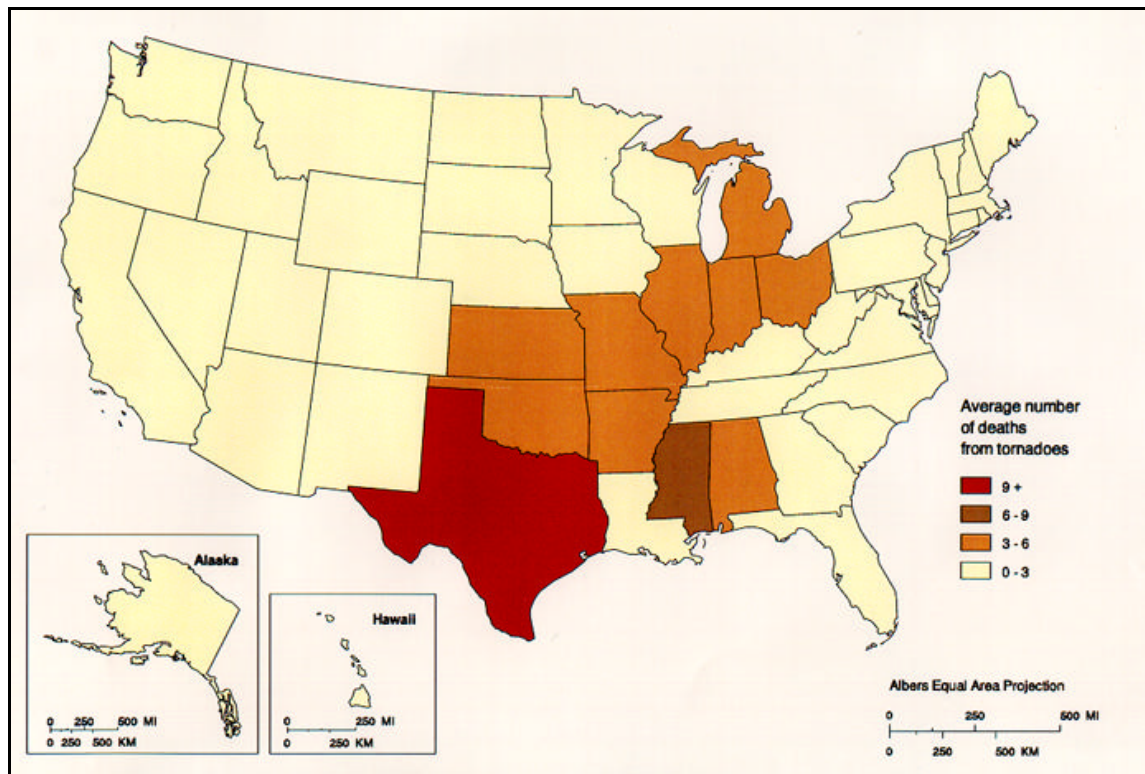
Map 3-3.   Average annual deaths by State caused by tornadoes: 1953-1993.
           Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
           Source: *Data from National Oceanic Atmospheric Administration, 1993.*

the highest annual average, 11 deaths, followed by Mississippi with 8 deaths. Four States had an annual average of five deaths during that period, and four others had an annual average of four deaths.

Between 1975 and 1995, 106 major Federal disaster declarations included impacts caused by tornadoes. The States with the greatest number of tornado-related disasters were: Mississippi (14); Alabama and Illinois (9 each); Oklahoma (8); Wisconsin (7); Ohio (6); and Missouri, Minnesota, Louisiana, Georgia, and Arkansas (5 each).

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

The NWS evaluates each major tornado to determine the accuracy of its predictions and identifications based on weather data obtained from radar and other sources, local tornado spotters, emergency operations personnel, law enforcement agencies, and the general public. The NWS goal is to improve its ability to warn affected populations. Local governments and the news media routinely evaluate their capabilities and to identify areas where improvements are needed in the warning process.

The research community surveys damaged areas to understand how structures perform. The purposes of this research are to reduce damage and save lives during future tornadoes, and to transfer information to critical sources.

Based on post-event analyses, photogrammetric determinations of the motion of objects caught up in tornadoes documented on film and videotape, and measurement of speeds of objects using Doppler radar, it has been determined that the maximum wind speed in a tornado occurs 100 to 150 ft (30 to 50 m) above the ground (Golden and Snow, 1991). From their points of origin, 54 percent of tornadoes travel northeasterly, 22 percent travel easterly, 22 percent travel southeasterly, 8 percent travel northerly, 2 percent northwesterly, and 1 percent travel southerly, westerly, and southwesterly, respectively (Twisdale, 1978).

Dr. Theodore Fujita, professor of meteorology at the University of Chicago, conducted research on the complicated structure of tornado winds. He first documented the "suction spots" phenomenon from an aerial damage survey of the 1965 Palm Sunday event. In addition to suction vortices, other asymmetric flow configurations have been documented (Golden and Snow, 1991).

Experts believe suction vortices may help explain why one structure is destroyed while an adjacent structure is basically untouched.

Within the research community, there is no agreement regarding what causes the destruction of buildings. Some experts believe the difference in atmospheric pressure inside and outside causes buildings to explode. Others believe destruction is caused by wind-induced forces that tear structures apart from the outside.

MITIGATION APPROACHES

Mitigation opportunities for tornado winds are similar to mitigation measures for other wind hazards. However, the damage associated with violent tornadoes due to extreme wind speeds and pressures may be difficult to mitigate in a cost-effective manner. Attention to the type of structure used in tornado-prone areas may yield benefits, particularly by avoiding highly susceptible manufactured or mobile homes.

The greatest protection is afforded by quality construction and reinforcement of walls, floors, and ceilings. Proper anchoring of walls to foundations and roofs to walls is essential for a building to withstand certain wind speeds. In tornado damage studies, the wind engineering research community has found considerable variability in construction quality and material (Golden and Snow 1991). Code adoption by local jurisdictions, compliance by builders, and local government inspection of new homes could reduce the risk of destruction in tornado-prone areas.

Loss of life and injuries may be reduced if more individuals seek shelter in basements, small interior rooms, or hallways, and avoid rooms and buildings with large roof spans. An interior room or closet has less chance of collapse or failure than other areas. A reinforced, in-residence tornado shelter may be constructed for approximately $6,000 (1995 value), while the cost of retrofitting an interior room or closet in an existing house would be approximately $3,000 (Golden and Snow, 1991).

NOAA Natural Disaster Survey Reports highlight the need for local emergency managers, law enforcement officials, and local tornado spotters to provide information regarding tornado touchdowns. This allows NWS to quantify its radar findings and improve subsequent tornado watches and warnings.

RECOMMENDATIONS

Recommendations for reducing life safety risks associated with tornado events are identified in NOAA's Natural Disaster Reports, including:

- Improve radio and wire communications with the media and local emergency managers;

- Equip gathering places with weather radios with an audible alert of warning and require testing of response and preparedness plans;

- Continue awareness and preparedness efforts in schools; and

- Make special efforts to inform mobile homes residents about the impacts of the tornado hazard as well as locations of safe shelters in times of emergency.

BIBLIOGRAPHY AND REFERENCES

Angel, W. 1993. *National Summary of Tornadoes, 1993.* NOAA, National Environmental Satellite Data and Information Service, National Climatic Data Center.

Byrant, E. 1991. *Natural Disasters*. New York, NY: Cambridge University Press.

Coch, N.K. 1995. *GEOHAZARDS: Natural and Human*. Upper Saddle River, NJ: Prentice Hall.

Galway, J.G. June 1981. "Ten Famous Tornado Outbreaks." *Weatherwise Magazine*.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." *Reviews of Geophysics.* American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

National Weather Service. 1994. *Natural Disaster Survey Report: Southeastern United States Palm Sunday Tornado Outbreak of March 27, 1994*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1993. *Natural Disaster Survey Report: The Widespread November 21-23, 1992, Tornado Outbreak—Houston to Raleigh and Gulf Coast to Ohio Valley*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1993. *Natural Disaster Survey Report: Tampa Bay Tornadoes—October 3, 1992*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1991. *Natural Disaster Survey Report: Wichita/Andover, KS, Tornado, April 26, 1991*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1991. *Natural Disaster Survey Report: The Plainfield/Crest Hill Tornado—Northern Illinois—August 28, 1990*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

National Weather Service. 1992. *Tornadoes: Nature's Most Violent Storms*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Ramsdell, J.V., and G.L. Andrews. 1986. *Tornado Climatology of the Contiguous United States*. U.S. Department of Commerce, Pacific Northwest Laboratory, prepared for U.S. Nuclear Regulatory Commission.

Twisdale, L.A., and W.L. Dunn. 1983. "Wind Loading from Multivortex Tornadoes." *Journal of Structural Engineering.* American Society of Civil Engineers. Vol. 109, No. 8, pp. 2016-2022.

Twisdale, L.A., and W.L. Dunn. 1983. "Probabilistic Analysis of Tornado Wind Risks." *Journal of Structural Engineering.* American Society of Civil Engineers. Vol. 109, No. 2, pp. 468-488.

Twisdale, L.A. 1978. "Tornado Data Characterization and Windspeed Risk." *Journal of the Structural Division*. American Society of Civil Engineers. Vol. 104, No. ST10, pp. 1611-1630.

WINDSTORMS

Chapter Summary

Extreme winds other than tornados are experienced in all regions of the United States and its territories. Areas experiencing the highest wind speeds are coastal regions from Texas to Maine, under the influence of North Atlantic Ocean and Gulf of Mexico hurricane-related windstorms, and the Alaskan coast, under the influence of winter low-pressure systems in the Gulf of Alaska and North Pacific Ocean. Isolated wind phenomena in the Western States, such as the Chinook and Santa Ana winds, occur very locally along mountainous terrains.

It is difficult to separate the various wind components that cause damage from other wind-related natural events that often occur with or generate windstorms. For example, hurricanes with intense winds often spawn numerous tornados or generate severe thunderstorms producing strong, localized downdrafts.

Windstorms and wind-related events caused 63 fatalities in 1993. Florida suffered the highest number of deaths, 10. From 1981 to 1990, the insurance industry spent nearly $23 billion on wind-related catastrophic events. Over the past 20 years, 193 Federal disaster declarations involved wind-induced damage.

A project developed by the Wind Engineering Research Center at the Texas Tech University in Lubbock, TX and the Insurance Institute for Property Loss Reduction in Wheaton, IL created a new wind-resistance classification system for buildings (IIPLR, 1994). It allows owners to identify corrective actions needed to make buildings safer, and helps officials to pinpoint buildings for evacuation during windstorms.

Improved building codes, retrofitting, and land use are some mitigation approaches used to limit exposure to windstorms. Recently, the National Research Council urged that a National Wind Science and Engineering Program be implemented to revitalize wind-hazard research (NRC, 1993).

Photo: Red Cross

HAZARD IDENTIFICATION

Wind is defined as the motion of air relative to the earth's surface (Golden and Snow, 1991). The horizontal component of the three-dimensional flow and the near-surface wind phenomenon are the most significant aspects of the hazard. Extreme windstorm events are associated with extratropical and tropical cyclones, winter cyclones, and severe thunderstorms and accompanying mesoscale offspring such as tornados and downbursts (Golden and Snow, 1991). Winds vary from zero at ground level to 200 mph (89 m/s) in the upper atmospheric jet stream at 6 to 8 mi (10 to 13 km) above the earth's surface.

The damaging effects of windstorms associated with hurricanes may extend for distances in excess of 100 mi (160 km) from the center of storm activity. Isolated wind phenomena in the mountainous western regions have more localized effects.

In the mainland United States, the mean annual wind speed is reported to be 8 to 12 mph (4 to 5 m/s), with frequent speeds of 50 mph (22 m/s) and occasional wind speeds of greater than 70 mph (31 m/s). For coastal areas from Texas to Maine, tropical cyclone winds may exceed 100 mph (45 m/s).

Large-scale extreme wind phenomena are experienced over every region of the United States and its territories. Additional wind hazards occur on a very localized level due to downslope windstorms along mountainous terrains, such as the Chinook winds along the eastern slope of the Rocky Mountains in Montana, New Mexico, Colorado, and Wyoming, and the Santa Ana winds of southern California. These regional phenomena, known as foehn-type winds, result in winds exceeding 100 mph (45 m/s), but they are of short duration and affect a relatively small geographic area.

The Santa Ana winds only impact southern California. They generally occur during the late summer to early winter and are generated when the passage of dry, cold weather frontal systems is followed by a high pressure system developing over the Utah-Nevada area. The western flow of the cooler air mass loses moisture as it is forced to the west and funneled down through mountain passes along the western slopes of the mountains. With the rapid temperature increase as the winds descend, 5.5°F for every 1,000 ft or 304 m of descent, the Santa Ana winds become very dry, hot, and fast.

The Chinook winds along the eastern slopes of the Rocky Mountains occur during the winter as a result of large atmospheric movement over mountain ridges.

The downslope winds along the eastern side gather strong near-surface speeds, with record wind gusts up to 140 mph (63 m/s) measured in Boulder, Colorado. Other notable mountain windstorm events, such as Oregon's Columbia River Gorge winds and Utah's Wasatch Mountain winds, occur during cold fronts, when cold air masses funnel down through canyons.

Severe thunderstorms also produce wind downbursts and microbursts, as well as tornados. Severe windstorms result in as many as 1,000 tornados annually (Golden and Snow, 1991). NWS uses the NEXRAD Severe Weather Potential algorithm as an automated procedure to detect severe local storms and to forecast the potential for tornados, hail, and heavy rainfall (Kitzmiller, McGovern, and Saffle, 1992).

It is difficult to separate the various wind components that cause damage during a windstorm. For example, hurricanes have high winds rotating around the eye of the storm, spawn numerous tornados, and generate severe thunderstorms producing strong, localized downdrafts (downbursts and microbursts) (Golden and Snow, 1991).
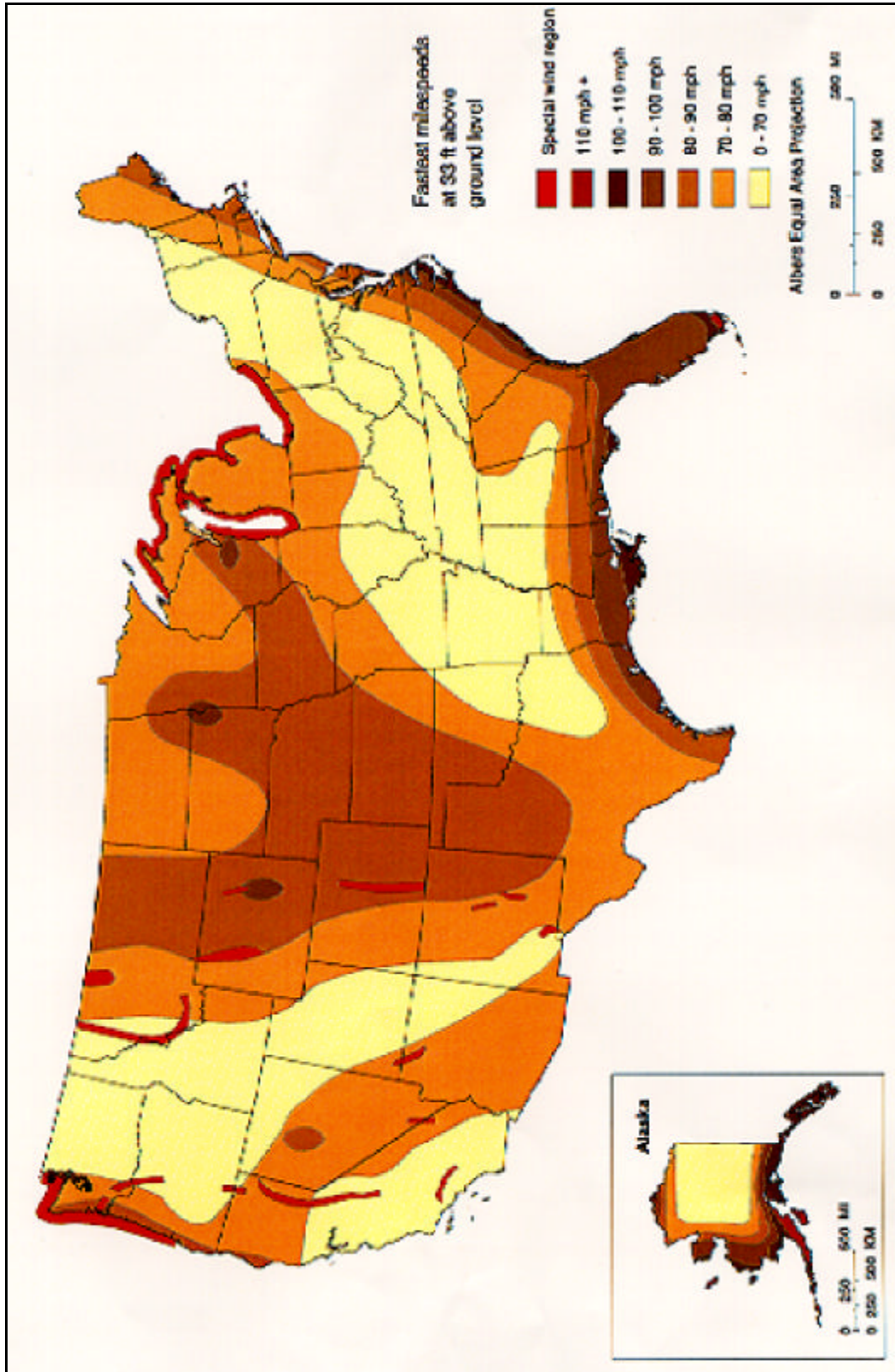
RISK ASSESSMENT

Probability and Frequency

Wind climatology and geographic distribution of wind-speed variations are commonly associated with unique regional climatic and meteorological characteristics and seasonal patterns (Map 4-1). Coastal regions from Texas to North Carolina may experience intense winds from hurricanes and tropical storms. Most of Florida is susceptible to winds in excess of 100 mph (45 m/s) on a regular basis.

Wind climatology depicted on Map 4-1 shows the fastest mile wind speeds expected to be encountered with a return period interval of 50 years, an annual probability of 0.002. Certain regions of the United States have been identified and specially designated because wind speeds faster than 70 mph (31 m/s) occur more frequently than the 50-year return period, or there are special high wind features such as downslope winds (western United States) or lake-effect winds (Great Lakes region).

Exposure

Areas experiencing the highest wind speeds are coastal regions from Texas to Maine, under the influence of North Atlantic Ocean and Gulf of Mexico windstorms associated with tropical cyclones, and the Alaskan

Fastest milespeeds at 33 ft above ground level

Special wind region

110 mph +

100 - 110 mph

90 - 100 mph

80 - 90 mph

70 - 80 mph

0 - 70 mph

Albers Equal Area Projection

Alaska

Map 4-1.   Wind climatology for the United States for special high wind regions and 50-year return period fastest mile speeds. Data not available for Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories. Source: *Data from American National Standards Institute, 1982.*

coast, under the influence of winter low-pressure-system windstorms in the Gulf of Alaska and North Pacific Ocean.

Property damage and loss of life from windstorms are increasing due to a variety of factors. Use of manufactured housing is on an upward trend, and this type of structure provides less resistance to wind than conventional construction. Uniform building codes for wind-resistant construction are not adopted by all States, and population trends show rapid growth in the highly exposed areas of the coastal zone from Texas to Maine.

Because of continued growth of the population in the coastal States susceptible to high winds from tropical cyclones, the deteriorating condition of older homes, and the increased use of aluminum-clad mobile homes, the impacts of wind hazards will likely continue to increase. The general design and construction of buildings in many high wind zones do not fully consider wind resistance and its importance to survival.

Consequences

Near-surface winds and associated pressure effects, positive, negative, and internal, exert pressure on structure walls, doors, windows, and roofs, causing the structural components to fail. Positive wind pressure is a direct and frontal assault on a structure, pushing walls, doors, and windows inward. Negative pressure affects the sides and roof where passing currents create lift and suction forces that act to pull building components and surfaces outward. The effects of winds are magnified in the upper levels of multi-storey structures.

Just as positive and negative forces impact and remove a windward protective building envelope (i.e., doors, windows, walls), internal pressures rise and result in roof or leeward building component failures and considerable structural damage or collapse. Debris carried along by extreme winds can directly contribute to loss of life and indirectly to the failure of protective building envelope components. Upon impact, wind-driven debris can rupture a building, allowing more significant positive and internal pressures.

The insurance industry spent nearly $23 billion on wind-related catastrophic events from 1981 to 1990 (NRC, 1993). Of the three primary sources, hurricanes and tropical storms, severe thunderstorms, and winter-storms, severe local windstorms accounted for 51.3 percent of the expenditures. Windstorms in 1993 resulted in 40 fatalities, 129 injuries, and $231 million in damage, while thunderstorm/wind events resulted in 23 fatalities, 458 injuries, and $349 million in damage (NOAA, 1994).

The NWS reported a significant increase in wind-related fatalities between 1992 and 1993, from 28 to 63. Of the deaths, 74 percent occurred in open areas and in vehicles.

From June 1975 to May 1995, 193 Federal disaster declarations involved wind-induced natural hazards: 106 for s, 40 for hurricanes and tropical storms, 25 for typhoons, and 22 for high winds.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Key research on wind has been conducted by NWS branches and the Wind Engineering Research Center (WERC) at Texas Tech University, in conjunction with the Wind Damage Mitigation Committee of the Insurance Institute for Property Loss Reduction (IIPLR) and Dr. Theodore Fujita of the University of Chicago. Dr. Fujita's significant contributions to wind research include the development of the Fujita Scale to classify tornados, and the recent evaluation and assessment of downburst wind damages occurring with extreme thunderstorm and windstorm events, such as experienced in Kauai, HI during Hurricane Iniki in 1992.

The NWS modernization program and the deployment and implementation of the wind-measuring system NEXRAD has improved the operational observation program and the climatology database. NEXRAD enhances the ability to predict downbursts and wind shears near airports. The data prompt development of frequency-of-occurrence data for mesocyclones, the typical wind circulation environment exhibited prior to the development of a tornado or severe thunderstorm/wind event (NRC, 1993).

A WERC/IIPLR project developed an alternative to the wind-resistance classification system used by the Insurance Services Offices which correlates a building's wind resistance with fire resistance. The WERC/IIPLR classification system identifies the wind resistance capabilities of a building based on building type (material used and system employed during construction) and other related factors pertaining to environment, frame, roof envelope, wall envelope, and other considerations (IIPLR, 1994). The system allows for evaluation of the weak points of existing buildings, enabling owners to take appropriate corrective actions to make buildings safer. The system can be used to identify individual buildings for evacuation because of poor resistivity.

Published reports on U.S. windstorm hazards discuss damages and include maps of the severity and extent of various types of extreme events (Golden and Snow,

1991; NRC, 1993). Updated information on the number of occurrences of windstorms is acquired continually by the NWS on a national and State-by-State basis.

MITIGATION APPROACHES

Improved and consistent building codes have been recommended as a key measure to mitigate life and property losses associated with windstorms (NRC, 1993). Adoption, enforcement, and compliance with a unified code for all regions of the United States would help ensure construction standards needed to build structures resistant to the lateral loads and uplift forces of severe winds. Improvements could be made to structural cladding, shuttering systems, and materials that are resistant to the penetration of wind-blown debris and projectiles.

In addition to improved construction standards, land-use regulations in the regions susceptible to windstorm hazards could limit exposure. Zoning as a form of land-use management and control can regulate populations and residential, commercial, and industrial developments in locations of known high risk exposure. It also can be used to reduce building density, adjust timing of regional development plans, and define the type of developments allowable in these hazard areas (NRC, 1993).

RECOMMENDATIONS

The National Research Council's publication on windstorm hazards, *Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation* (1993), presents several categories of recommendations: wind hazards and related issues; nature of wind; wind engineering; mitigation, preparedness, response and recovery; education and technology transfer; and cooperative efforts. The report identifies the establishment of a National Wind Science and Engineering Program as a critical element necessary to "revitalize wind-hazard research."

BIBLIOGRAPHY AND REFERENCES

American National Standards Institute. 1982. ***Building Code Requirements for Minimum Design Loads on Buildings and Other Structures.*** ANSI A58.1. New York, NY: American Society of Civil Engineers.

American Society of Civil Engineers. 1993. ***Minimum Design Loads for Building Other Structures.*** ASCE, July, 1993. New York, NY.

Brinkmann, Waltraud A.R. 1975. ***Local Windstorm in the United States: A Research Assessment.*** Institute of Behavioral Science, The University of Colorado, Boulder, CO.

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Chagnon, S.A., and J.M. Chagnon. 1992. "Storm Catastrophes in the United States." ***Natural Hazards***, Vol. 6, No. 2, pp. 93-107.

Finkl, C. W., Jr. (ed.). 1994. ***Journal of Coastal Research, Special Issue No. 12. Coastal Hazards: Perception, Susceptibility and Mitigation***. The Coastal Education and Research Foundation, Inc.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." ***Reviews of Geophysics.*** American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Insurance Institute for Property Loss Reduction. 1994. ***Understanding the Wind Peril.***

Kitsmiller, D.H., W.E. McGovern, and R.E. Saffle. February 1992. ***The NEXRAD Severe Weather Potential Algorithm.*** NOAA Technical Memorandum, NWS TDL 81. Silver Spring, MD: Techniques Development Laboratory.

National Research Council. 1993. ***Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation.***

National Weather Service. 1994. ***Thunderstorms and Lightning: The Underrated Killers.*** U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Ramsdell, J.V., D.L. Elliott, C.G. Holladay, and J.M. Hubbe. 1986. ***Methodology for Estimating Extreme Winds for Probabilistic Risk Assessments.*** Washington, DC: U.S. Nuclear Regulatory Commission.

Twisdale, L.A., and P.J. Vickery. 1993. "Analysis of Thunderstorm Occurrences and Windspeed Statistics." In: ***Proceedings of the 7th U.S. National Conference on Wind Engineering.*** Los Angeles, CA: University of California.

Twisdale, L.A. October 1988. "Probability of Facility Damage from Extreme Wind Effects." ***Journal of Structural Engineering.*** American Society of Civil Engineers. Vol. 114, No. 10, pp. 2190-2209.

HAILSTORMS

Chapter Summary

Hailstorms develop from severe thunderstorms. Although they occur in every State on the mainland United States, hailstorms occur primarily in the Midwestern States. Only a localized area along the border of northern Colorado and southern Wyoming experiences hailstorms on 8 or more days each year. Most inland regions experience hailstorms at least 2 or more days each year.

Hailstorms cause nearly $1 billion in property and crop damage annually, as peak activity coincides with the Midwest's peak agricultural seasons. Long-stemmed vegetation is particularly vulnerable to damage by hail impact and accompanying winds. Severe hailstorms also cause considerable damage to buildings and automobiles, but rarely result in loss of life.

Efforts to reduce hailstorm damage generally are associated with mitigation activities for thunderstorms and windstorms, including building code improvement and enforcement and public awareness and education campaigns. Improvements in weather warning systems will enhance the ability to predict severe thunder and hailstorms.

Photo: Red Cross

HAZARD IDENTIFICATION

A hailstorm is an outgrowth of a severe thunderstorm in which balls or irregularly shaped lumps of ice greater than 0.75 in (1.91 cm) in diameter fall with rain (Gokhale, 1975). Early in the developmental stages of a hailstorm, ice crystals form within a low-pressure front due to warm air rising rapidly into the upper atmosphere and the subsequent cooling of the air mass. Frozen droplets gradually accumulate on the ice crystals until, having developed sufficient weight, they fall as precipitation.

The size of hailstones is a direct function of the severity and size of the storm. High velocity updraft winds are required to keep hail in suspension in thunderclouds. The strength of the updraft is a function of the intensity of heating at the Earth's surface. Higher temperature gradients relative to elevation above the surface result in increased suspension time and hailstone size (Bryant, 1991).

RISK ASSESSMENT

The areal extent and severity of hailstorm hazards are different from thunderstorms or tornados. Hailstorms occur more frequently during the late spring and early summer, when the jet stream migrates northward across the Great Plains. This period has extreme temperature changes from the ground surface upward into the jet stream, which produce the strong updraft winds needed for hail formation.

Probability and Frequency

Data on the probability and frequency of occurrence of hailstorms is limited, with little recent research. However, in *Natural Hazards* (1991), Bryant presented a map depicting the annual frequencies of hailstorm occurrences in the United States (from Eagleman, 1983). Recreated in Map 5-1, it shows that only a localized area along the border of northern Colorado and southern Wyoming experiences hailstorms 8 or more days each year. Outside of the coastal regions, most of the United States experiences hailstorms at least 2 or more days each year.

The areal extent and severity of the hailstorm hazard is not coincident with maximum thunderstorm or tornado activity. The middle areas of the Great Plains are most frequently affected by hailstorms. Multiple impacts of concurrent severe thunderstorm effects from extreme winds, tornados, and hail are very likely in this region, even though the Great Plains is not where each of these hazards, taken individually, occurs with the greatest frequency.

Exposure

Peak periods for hailstorms, late spring and early summer, coincide with the Midwest's peak agricultural seasons for crops such as wheat, corn, barley, oats, rye, tobacco, and fruit trees. Long-stemmed vegetation is particularly vulnerable to damage by hail impacts and winds. Severe hailstorms also cause considerable damage to buildings and automobiles, but rarely result in loss of life.

The land area affected by individual hail events is not much smaller than that of a parent thunderstorm, an average of 15 mi (24 km) in diameter around the center of a storm (Pearce and others, 1993).

Consequences

The development of hailstorms from thunderstorm events causes nearly $1 billion in property and crop damage each year (NWS, 1994). Recent significant hailstorms include events in Denver, CO (1994) and in the eastern Texas-Oklahoma region (1995).

The Property Loss Research Bureau indicates that the April-May 1995 hailstorm in the Texas-Oklahoma region may have been the worst on record in terms of non-agricultural property losses. However, more specific information is not readily available.

The Midwest hailstorm and tornado event in April 1994 lasted 4 days. According to Property Claims Services in Rahway, NJ, it produced 300,000 damage claims against insurers, more than Hurricane Andrew or the Northridge earthquake.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Recent unpublished private research has used the hail dataset available from the National Climatic Data Center (NCDC) in Asheville, NC, to model hailstorm frequency and hailstone size. The model is geocoded into 6-mi (10-km) grid cells across the lower 48 States. When it is available to others, the hail model data may be integrated into existing geographic information systems to help develop a hail risk index methodology for identification of high-risk zones.
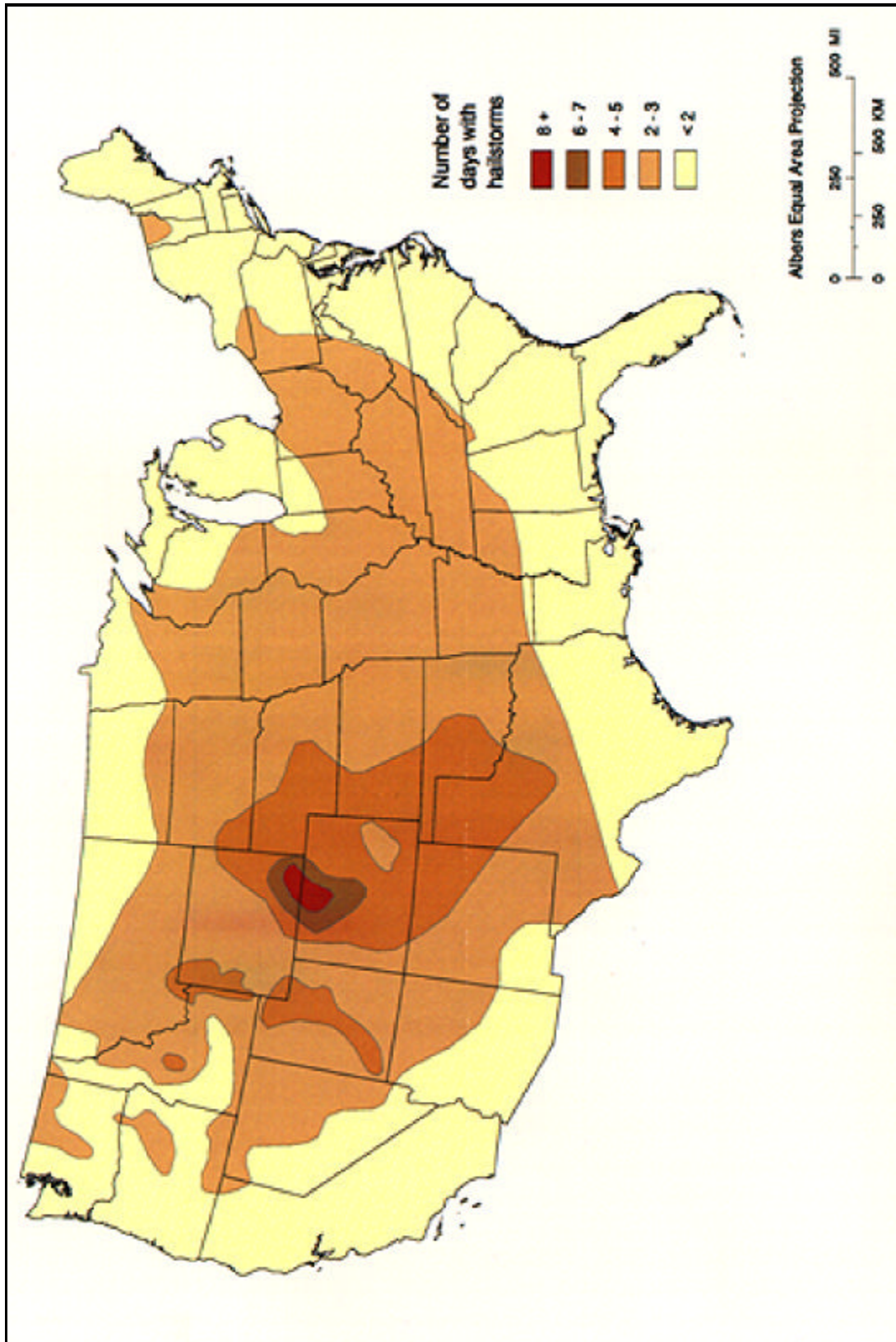
Map 5-1.   Annual frequency of hailstorms in the United States.
Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Data from Bryant, 1993, citing Eagleman, 1983.*

MITIGATION APPROACHES

Mitigation efforts to reduce hailstorm damage generally are similar to those associated with thunderstorm and windstorm hazards: building codes and public awareness and education campaigns. Weather warning system improvements and the modernization and implementation of NWS monitoring systems such as NEXRAD will improve prediction of the severe weather potential associated with thunderstorms and hailstorm development.

Seeding clouds with supercooled water containing silver iodide nuclei has been a hail suppression technique used around the world. Although it has reduced crop damage, the technique was discontinued in the United States in the early 1970s due to political controversy (Bryant, 1991).

RECOMMENDATIONS

Recent research on hailstorm hazards in the United States has not been published. Information collected by NCDC documents the annual incidence rate and damage. Recommendations on research, hazard mitigation, or hailstorm control were not found in available published reports.

In a June 1995 magazine article in *Business Geographics*, G. Mertz of DataMap, Inc., recommended the integration of the NCDC hail dataset into a geographic information system. A hailstorm exposure map and a hail index system could identify high- and low-risk areas. The index was discussed as a useful tool for FEMA and the insurance industry to evaluate exposure and risk for residential, automobile, crop, and business insurance ratings.

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. *Natural Hazards.* New York, NY: Cambridge University Press.

Eagleman, J.R. 1983. *Severe and Unusual Weather.* New York, NY: Van Nostran Reinhold.

Gokhale, N.R. 1975. *Hailstorms and Hailstone Growth.* Albany, NY: State University of New York Press.

Golden, J.H., and J.T. Snow. 1991. "Mitigation Against Extreme Windstorms." *Reviews of Geophysics.* American Geophysical Union. Vol. 29, No. 4, pp. 477-504.

Pearce, L., H. Hightower, B. Konkin, S. Megalos, and J. Pernu. 1993. *British Columbia: Hazard, Risk and Vulnerability Analysis*, Vol. 1. The Disaster Preparedness Resources Center, The University of British Columbia.
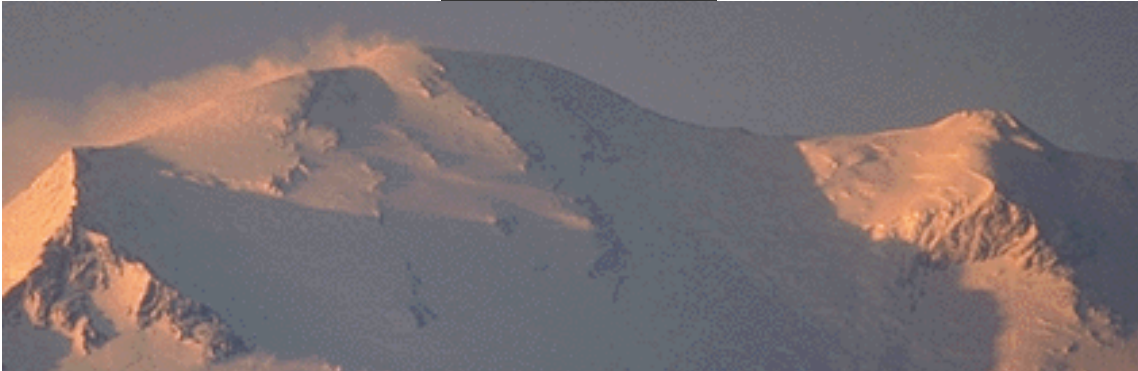
SNOW
AVALANCHES

Chapter Summary

Snow avalanches are not considered a major natural hazard because they impact relatively small areas of the United States. Compared with other hazards, snow avalanches have localized impacts and individually do not affect large numbers of people. However, the total number of deaths attributable to snow avalanches each year is exceeded only by those associated with floods, lightning, and tornadoes, and extreme heat.

Most of the 10,000 reported avalanches that occur each year are in remote, unpopulated mountainous areas, along recognized avalanche paths in previously identified hazard zones. The threat is most severe in the mountainous Western United States, including Alaska.

The sliding snow or ice mass in an avalanche moves at high velocities. It can shear trees, completely cover entire communities and highway routes, and level buildings. The primary threat is loss of life of back country skiers, climbers, and snowmobilers.

Since 1970, an average of 144 persons have been trapped in avalanches annually: on average 14 were injured and 14 died. The estimated annual average damage to structures is $500,000.

Recent avalanche mitigation approaches have included avalanche hazard zoning, evacuation, artificial release, and avalanche-control structures. Artificial release is the most common measure used in the United States. Where other methods are ineffective or cannot be used, control structures may be installed.

HAZARD IDENTIFICATION

A snow avalanche is a slope failure composed of a mass of rapidly moving, fluidized snow that slides down a mountainside. The flow can be composed of ice, water, soil, rock, and trees (Armstrong and Williams, 1992; NRC, 1990; Coch, 1995). The amount of damage depends on the type of avalanche, the composition and consistency of the material contained in the avalanche, the velocity and force of the flow, and the avalanche path.

The slope failure associated with an avalanche is caused by several factors, but is primarily due to large accumulations of snow on steep slopes. Avalanches occur on slopes averaging 25 to 50 degrees, and the majority start on slopes between 30 and 40 degrees. They are triggered by natural seismic or climatic factors such as earthquakes, thermal changes, and blizzards. Human factors, including snowmobiles, skiers, hikers, vehicle traffic, and elastic sound waves created by explosions can trigger events, as can direct dynamic loading from ice slabs falling off cornices (NRC, 1990).

Natural and human-induced snow avalanches most often result from structural weaknesses within the snowpack. They are caused by changes in the type and thickness of the snowcover layer resulting from thermal fluctuations or multiple snowfall events. The potential for a snow avalanche increases with significant temperature influences, which cause metamorphic crystal change in the snow layer, and with accumulations of dry and wet snow over time.

At the point where the shear forces of the overburdened upper layer overcome the resistant forces of the underlayer, the mass slips and begins sliding downslope. The intensity and impact of the resulting avalanche depend on the volume of snow accumulated in the upper layer, the density of the material, the slope of the starting area, the avalanche path, and the runout zone at the bottom of the slope.

Dry, low density avalanche releases can reach maximum velocities of 45 mph (20 m/s) to 157 mph (70 m/s), depending on the vertical fall distance (Mears, 1992). Slower estimated maximum velocities of 22 mph (10 m/s) to 78 mph (35 m/s) for similar vertical fall distances are reached by wet, high density avalanches which can be more destructive and exert greater impact forces on structures. The weight of moving, water-saturated snow can be 25 to 31 lb/ft³ (400 to 500 kg/m³) throughout the entire depth of an avalanche flow (Mears, 1992). The moving mass entrains rock, soil, and other solid debris.

The most common types of snow avalanches are loose-snow and slab avalanches. A loose-snow avalanche is composed of dry, fresh snow deposits that accumulate as a cohesionless and unstable mass atop a stable and cohesive snow or slick ice sublayer. A loose-snow avalanche releases when the shear force of its mass overcomes the underlying resistant forces of the cohesive layer.

A slab avalanche generally is composed of a thick, cohesive snowpack deposited or accumulated on top of a light, cohesionless snow layer or slick ice sublayer. At the starting surface or top of the slab, a deep fracture develops in the slope of well-bonded, cohesive snow. Fractures of more than 2 mi (3 km) in length have been observed, and they can reach across several starting zones. A slab avalanche release is usually triggered by turbulence or impulse waves. Release also occurs when the internal cohesive strength of the slab layer is greater than the bonding at the basal and lateral slab boundaries. As a release occurs, the slab accelerates, gaining mass and speed as it travels down the avalanche path.

An avalanche path is determined by the physical limitations of the boundaries of the local terrain and manmade features. An avalanche may follow a path along a channelized or confined terrain, similar to debris flows or streams, before spreading onto alluvial fans or gentle slopes. In other instances, avalanches follow unconfined or planar slopes of a mountain side down to the abrupt slope change of the valley bottom (Mears, 1992). The avalanche path itself varies in width as it transitions along the path, depending on the confinement of the terrain and the velocity of flow.

Mears (1992) describes the avalanche path as having three specific transition zones:

- The Starting Zone is typically located near the top of the ridge, bowl or canyon, with steep slopes of 25 to 50 degrees;

- The Track Zone is the reach with mild slopes of 15 to 30 degrees and the area where the avalanche will achieve maximum velocity and considerable mass; and

- The Runout Zone is the gentler slopes of 5 to 15 degrees located at the base of the path, where the avalanche decelerates and massive snow and debris deposition occurs.
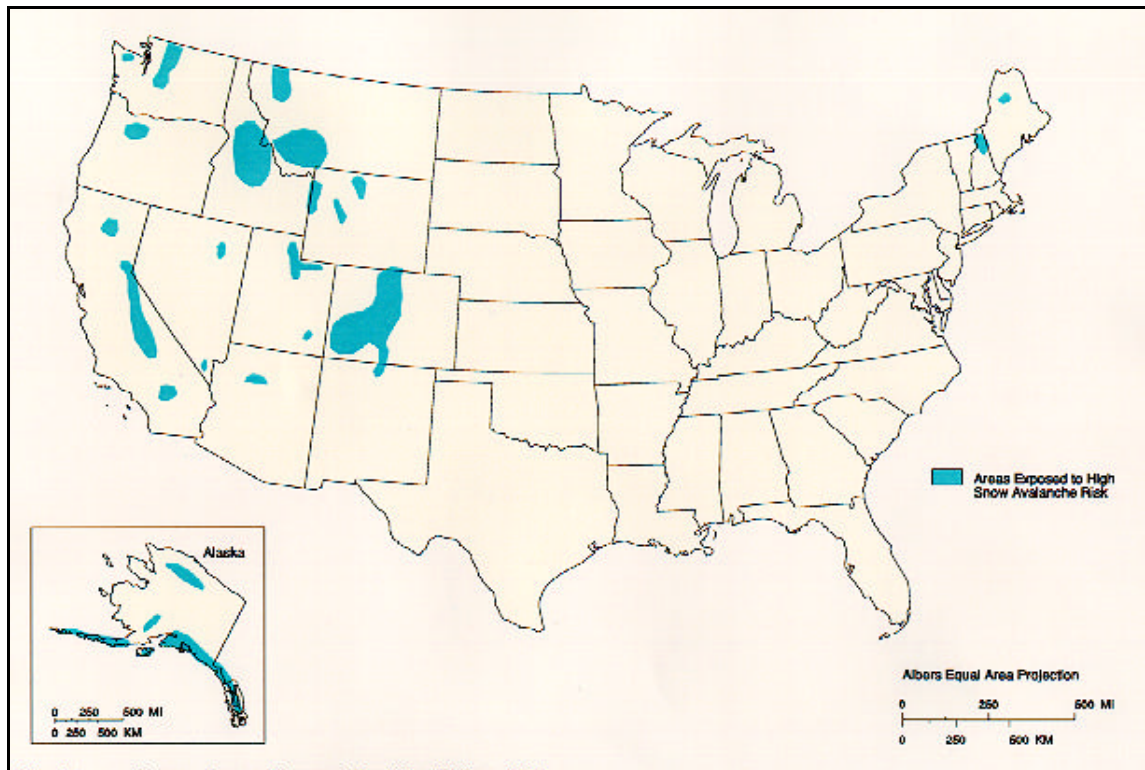
Map 6-1.   Qualitative indicator of the severity of snow avalanches in the United States.
Data not available for Puerto Rico, U.S. Virgin Islands, and Pacific Territories.
Source: *Personal Communications, Knox Williams, 1995.*

RISK ASSESSMENT

Snow avalanches in the United States have varying levels of severity, depending on slope steepness and snow accumulation. As shown on Map 6-1, the threat is most severe in the mountainous western States, including Alaska. New England mountains have a low level of avalanche risk, and the rest of the United States has no risk.

Snow avalanches occur throughout the winter and may flow down the same paths several times during a season. In avalanche-prone areas, most State and local officials maintain records of previous events and have documented repetitive paths. As a result, avalanche hazard zones can be identified in many areas.

Probability and Frequency

The geophysical processes that contribute to snow avalanches during a particular year are statistically independent of past events. However, like other similar natural processes, a return period and probability of occurrence can be developed from historical records.

Avalanche occurrence is not directly attributed to a specific major meteorological event, such as the 1-percent-annual-chance or 100-year snowfall. It is more commonly a result of a combination of weather and snow-pack conditions (Mears, 1992). Unfortunately, the short period of recorded and observed avalanches and associated conditions that contribute to the risk make it difficult to develop return periods for each avalanche-prone area in the United States.

The classification and delineation of avalanche hazard zones for Vail, CO, Ketchum, ID, and Juneau, AK, are similar to the Red and Blue Zones developed and used in the Swiss Alps. The Swiss zones are based on quantitative techniques for determining avalanche impact pressures and return periods. The Red Zone identifies areas of highest risk (NRC, 1990). Avalanches in Red Zones are either powerful (impact pressures greater than 630 lb/ft² (30kPa)) with a return period of 300 years or less, or all avalanches irrespective of intensity with return pereiods of up to 30 years. The Blue Zone identifies areas subject to less frequent avalanches with 30- to 300-year return periods, and impact pressures less than 630 lb/ft² (30 kPa).

Although the same zone designation system is used in the United States, the definition of each zone requires modification due to the short period of historical record. This limitation makes it more difficult to determine return periods for avalanches in most locations (Mears, 1992).

In the Colorado Geological Survey report on avalanches, *Snow Avalanche Hazard Analysis for Land-Use Planning and Engineering*, Mears discusses the techniques available to determine a return period for avalanches based on historic records, recent observations, aerial photography analyses, and vegetation characteristics (Mears, 1992). A snow avalanche will inflict damage and changes to the forests and vegetation along its path, unless they are protected by deep snowpack. Thus vegetation is a valuable tool in determining when previous events occurred. Vegetation indicators for avalanche frequency are listed in Table 6-1.

Avalanche activity along a path may be continuous throughout the season, in which case the annual probability of occurrence is constant regardless of the estimated return period of individual incidents. An encounter probability based on the relationship of the return period and annual probability was developed by LaChapelle (1966) to calculate the risk of an avalanche with a given return period occurring within a certain period of years. Even though the intensity and severity of an avalanche cannot be directly associated with a given frequency, return period, and encounter probability, the concepts are useful in land-use planning and engineering design.

Exposure

Back country skiers, backpackers, and snowmobilers in rural areas are at greatest risk of loss of life due to suffocation when buried in an avalanche. Avalanches can damage or destroy vehicles, highways, utilities, and buildings.

Most avalanches that affect people occur in and around mountain resorts used by winter recreational enthusiasts, while others affect downslope transportation routes and communities. Although the damage from avalanches is not as widespread as other natural hazards, on an annual basis fatalities exceed the average number of deaths due to all other hazards, except floods, lightning, tornadoes, and extreme heat.

The risk of avalanche loss is greatest on the flatter slope of the runout zone which is more conducive to development, transportation routes, and infrastructure. Exposure to the hazard has risen due to growth in winter recreational activities and resort facilities, mountain residences, highways, telecommunication lines, utilities, and mines in avalanche hazard zones.

Consequences

During the past two decades, snow avalanches have not prompted any federally-declared disasters, primarily because they tend to occur in areas with little development. Other reasons are improved and modernized monitoring techniques, awareness of the hazard, and remedial measures implemented to mitigate disaster potential. However, avalanches are still considered a prevalent hazard throughout the Rocky Mountain, Pacific Northwest, and Alaskan regions, with numerous incidents of property damage, injury, and death each year. From 1990 to 1995, 640 avalanches in the United States impacted individuals and property.

Only approximately 10,000 of the estimated 100,000 snow avalanches that occur each year are reported. Since 1970, an average of 144 persons have been trapped in avalanches annually, causing an annual average of 14 injuries and 14 deaths. Skiers, snowmobilers, and climbers in wooded and sloped areas in avalanche zones are most vulnerable (Armstrong and Williams, 1992). For many avalanches in which people have suffered injuries or loss of life, the triggering mechanism for the avalanche has been the victims themselves.

In the winter of 1994–95, California had more snow avalanches than any other State, with 4,787 reported at seven locations. However, over the 10 years from the winter of 1985–86 through the winter of 1994–95, Colorado's 65 fatalities were the highest. The activity with the high-

TABLE 6-1.—*Vegetation as an avalanche-frequency indicator*

Return Period	Vegetation Indicators
1-10 years	Track supports grasses, shrubs, flexible trees up to 6.5 ft. (2m) high; broken timber on ground and at path boundaries
10-30 years	Predominantly pioneer species; young trees similar to adjacent forest; broken timber on ground at path boundaries
30-100 years	Old uniform-aged trees of pioneer species; young trees of local climax species; old and partially decomposed debris
100-300 years	Mature, uniform-aged trees of local climax species; debris completely decomposed; increment core data required.

Source: *Mears, 1992.*

est fatality rate for the same period was back-country skiing, with 45 fatalities, followed by climbing, with 28 (Colorado Avalanche Information Center, 1995, unpublished).

Possibly the worst U.S. avalanche disaster occurred on March 1, 1910, in Wellington, WA. The avalanche derailed two trains, killing 96 persons (Armstrong and Williams, 1992).

TABLE 6-2.—*Avalanche Impact pressures related to damage.*

Impact Pressure		Potential Damage
kPa	lbs/ft^2	
2-4	40-80	Break windows
3-6	60-100	Push in doors, damage walls, roofs
10	200	Severely damage wood frame structures
20-30	400-600	Destroy wood-frame structures, break trees
50-100	1000-2000	Destroy mature forests
>300	>6000	Move large boulders

Source: *Mears, 1992.*

Property damage associated with avalanches is a function of several factors. Large external lateral loads can cause significant damage to structures and facilities. Table 6-2 indicates the estimated potential damage that can be expected for a given range of impact pressures.

A breakdown of costs associated with all types of property damage due to snow avalanches is not available. The estimated average annual damage to buildings alone is $500,000. However, a tally of the impact on public property, includes forests and parkland, transportation routes, and utilities, coupled with the cost of litigation following injuries or deaths, raises the estimated annual cost of avalanches to more than $5 million.

NRC (1990) offers examples of avalanche damage described below:

• Avalanches cost the Washington State Department of Transportation an estimated $330,000 each year for avalanche control, snow removal, and plowing, not including salaries and expenses of State employees.

• Between 1977 and 1986, avalanche damages in Alaska were estimated to be $11.4 million.

• On March 31, 1981, an avalanche at California's Alpine Meadows ski resort area resulted in seven deaths and caused approximately $1.5 million in property damage. Litigation and out-of-court settlements sent the cost spiraling to $14 million.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Snowstorms and ice storms are monitored daily by weather observation centers and a network of State and regional avalanche forecast centers for Colorado, Utah, Montana, Washington, Oregon, and Wyoming. Data collection methodologies on the number and location of snowfalls improve with each passing storm. Prevailing wind direction and temperature fluctuations are analyzed to assess the probability of avalanches in high-risk areas.

These methods are not completely effective in identifying potential avalanche hazard zones. In areas with known historical avalanche paths, the impact of the hazard may be mitigated by local experience and understanding of the hazard and triggering mechanisms. This knowledge makes the forecast and prediction process more reliable and enhances the effectiveness of warnings.

Forecasting avalanches can be accomplished by different methods with varying degrees of success. As warranted by climatic conditions, various methods are used. Weather forecasting of snowfall amounts, winds, and temperature are important tools to analyze snowpack conditions and avalanche potential for large geographic areas.

Local area avalanche forecasting involves snow pit analysis. This technique requires assessing sublayer conditions and the composition of each layer to detect the existence of unstable boundaries between cohesive and cohesionless snow and ice layers.

Large-scale computer-based forecasting methods require a historical and statistical database. Regional avalanche centers collect data on snow avalanches from a network of measuring sites. Nationwide programs for computer-based forecasting do not exist.

MITIGATION APPROACHES

Hazard mitigation efforts have been successful in reducing the exposure of people and property to snow avalanche hazards. Warnings are issued through radio and television, and posted, if possible, on bulletin boards in avalanche hazard areas.

The potential for property damage has prompted local avalanche zoning ordinances in California, Colorado, Idaho, Utah, and Washington. For example, hazard zones have been established in Vail, CO, and Ketchum, ID, based on avalanche studies and assessments (Armstrong and Williams, 1992; Mears, 1992). They are delineated and mapped based on historic evidence, recorded seasonal events, and terrain features that indicate the potential for event occurrence. In Vail, avalanche zones have been adopted in the City's comprehensive land-use plan and are used to evaluate proposed residential and commercial development.

To regulate land use effectively and to reduce the risk of damage from avalanches, hazard zones may be adopted in local ordinances. As a result of legislation passed in 1974, many avalanche-prone counties in Colorado have hazard plans or land-use rules that specifically address avalanche hazards. Even though Juneau, AK had determined its avalanche hazard zones based on studies and a geophysical investigation in the 1970s, and despite numerous avalanches, as of 1991 it had not adopted a zoning ordinance to regulate at-risk development (Armstrong and Williams, 1992).

The key mitigation recommendations in the Colorado Geological Survey's Bulletin 49 (1992) to either eliminate or reduce the hazard include avalanche hazard zoning, evacuation, artificial release, and avalanche-control structures. Artificial release is the most common measure used in the United States, but it is not 100-percent effective.

Control structures are used in areas where snow avalanches are unavoidable and other measures are ineffective or cannot be employed. Structures currently in use include supporting structures, snow-drift fences, deflecting berms, catching berms, catching structures, and direct-protection structures. Mechanical compaction and disruption of the cohesive slabs compresses or densifies the snow to strengthen the slope. It is commonly employed in ski resort areas to stabilize snow in starting zones (NRC, 1990).

RECOMMENDATIONS

The recommendations presented by NRC have addressed issues related to national leadership, hazard delineation and regulation, control measures, forecasting, research, and communications (NRC, 1990). NRC recognized snow avalanches as the "most frequent catastrophic mass movement in the Nation" and one of many components leading to extensive ground-failure hazards.

NRC concluded that, even though snow avalanches are the greatest natural hazard affecting winter activities in mountainous regions, the hazard receives little attention. Greater funding support is needed in order to better understand, predict, and mitigate snow avalanche hazards, and to educate local officials and emergency managers.

BIBLIOGRAPHY AND REFERENCES

Armstrong, B.R., and K. Williams. 1992. *The Avalanche Book, Revised and Updated.* Golden, CO: Fulcrum Publishing.

Byrant, E. 1991. *Natural Disasters.* New York, NY: Cambridge University Press.

Coch, N.K. 1995. *GEOHAZARDS: Natural and Human.* Upper Saddle River, NJ: Prentice Hall.

Colorado Avalanche Information Center (unpublished report). 1995. Denver, CO: Colorado Department of Natural Resources.

La Chapelle, E.R. 1966. *Encounter Probabilities for Avalanche Damage.* U.S. Department of Agriculture, Forest Service, Alta Avalanche Study Center. Miscellaneous Report No. 10.

Mears, A.I. 1989. "Regional Comparisons of Avalanche-Profile and Runout Data." *Arctic and Alpine Research.* Vol. 21, No. 3, pp. 232-238.

Mears, A.I. 1992. "Snow Avalanche Hazard Analysis for Land-Use Planning and Engineering." *Colorado Geological Survey Bulletin No 49.* Denver, CO: Department of Natural Resources.

National Research Council. 1990. *Snow Avalanche Hazards and Mitigation in the United States.* Washington D.C.: National Academy Press.

Perla, R., T.T. Cheng, and D.M. McClung. 1980. "A Two-Parameter Model of Snow-Avalanche Motion." *Journal of Glaciology.* Vol. 26, No. 94, pp.197-208.

Perla, R., K. Lied, and K. Kristensen. 1984. "Particle Simulation of Snow Avalanche Motion." *Cold Regions Science and Technology.* Vol. 9, pp. 191-202.

Salm, B., A. Burkard, and H. Gubler. 1990. *Berechnung von Fliesslawinen eine Anleitung fur Praktiker mit Beispeilen:* Mitteilungen des Eidgenossischen Istituts fur Schnee-und Lawinenforschung. No. 47, pp. 37.

Williams, K. Personal Communication, 1995. Fort Collins, CO: Colorado Avalanche Information Center.

SEVERE WINTERSTORMS

Chapter Summary

Winterstorms consisting of extreme cold and heavy concentrations of snowfall or ice affect every State in the continental United States and Alaska. Areas where such weather is rare, such as the extreme South, are disrupted more severely by winterstorms than are regions that experience severe weather more frequently.

Winterstorms are known to spawn other natural hazards, such as coastal flooding and erosion, severe thunderstorms and tornados, and extreme winds. These effects disrupt commerce and transportation and often result in loss of life due to accidents or hypothermia.

Between 1988 and 1991, a total of 372 deaths, an average of 93 each year, was attributed to severe winterstorms. The Superstorm of March 1993, considered among the worst non-tropical weather events in the United States, killed at least 79 people, injured more than 600, and caused $2 billion in property damage across portions of 20 States and the District of Columbia.

Experience has shown that no area can fully prepare for severe winterstorms. The March 1993 Superstorm was one of the most widely forecast severe winter events, yet it devastated many parts of the Eastern United States for more than a week.

Photo: Red Cross

Photo: Red Cross

HAZARD IDENTIFICATION

Winterstorms and blizzards originate as mid-latitude depressions or cyclonic weather systems, sometimes following the meandering path of the jet stream (Bryant, 1991). A blizzard combines heavy snowfall, high winds, extreme cold, and ice storms. The origins of the weather patterns that cause severe winterstorms, such as snowstorms, blizzards, and ice storms, are primarily from four sources in the continental United States.

In the Northwestern States, cyclonic weather systems from the North Pacific Ocean or the Aleutian Island region sweep in as massive low-pressure systems with heavy snow and blizzards. In the Midwestern and Upper Plains States, Canadian and Arctic cold fronts push ice and snow deep into the interior region and, in some instances, all the way down to Florida. In the Northeast, lake effect snowstorms develop from the passage of cold air over the relatively warm surfaces of the Great Lakes, causing heavy snowfall and blizzard conditions. The Eastern and Northeastern States are affected by extra-tropical cyclonic weather systems in the Atlantic Ocean and Gulf of Mexico that produce snow, ice storms, and occasional blizzards.

Many winter depressions give rise to exceptionally heavy rain and widespread flooding and conditions worsen if the precipitation falls in the form of snow. Snow volume exceeds that of rain by a factor of 7 to 10. Affected regions may be subjected to heavy snowfall. The winterstorm season varies widely, depending on latitude, altitude, and proximity to moderating influences.

Severe winterstorms have affected every State in the continental United States and Alaska. Hawaii, Puerto Rico, the U.S. Virgin Islands, and the Pacific territories are not affected by this hazard.

RISK ASSESSMENT

Probability and Frequency

Analysis of recorded snow level (depth) data can yield probability and frequency of occurrence associated with severe winterstorms. Snow level measurements are recorded each day at sites within the conterminous United States and Alaska. Snow level is an indicator of severity of winterstorms based on accumulation and associated snow loading. The weight of accumulated snow or ice results in snow load forces that can cause building collapse and damage to infrastructure.

Map 7-1 shows the probability of a snow of given depth (in centimeters) occurring within geographic areas of the conterminous United States with a 5-percent chance of being equaled or exceeded in a given year. The map is based on daily recorded data by the U.S. Department of Commerce's National Climatic Data Center in Asheville, NC and the U.S. Department of Energy's National Renewable Energy Laboratory in Golden, CO. The data are available in a 1993 CD-ROM entitled *Solar and Meteorological Surface Observation Network 1961-1990* (NCDC, 1993).

Regional studies of the mean annual snowfall for the Northeastern United States and the Great Lakes States show that the mean distribution of seasonal snowfall depends on latitude. Seasonal mean snowfall amounts range from 5.85 in (15 cm) in Virginia to more than 98 in (250 cm) in the New England States, New York, and West Virginia (Kocin and Uccellini, 1990). To establish the relationship between probability and frequency of occurrence for snowfall, historical records are analyzed for snowfall totals, ice accumulation, and the number and location of severe winterstorms.

Exposure

Nearly the entire United States, except the extreme southern States, Hawaii, and the U.S. territories, are considered at risk for severe winterstorms. The degree of exposure depends on the normal severity of local winter weather.

All of Alaska and some areas of the continental United States tend to be more susceptible than others to severe winterstorms, including the Upper Midwestern and Northeastern States. Generally, these regions are more prepared for severe winter weather. Those areas where such weather is rare are more likely to experience damage and disruptions when winterstorms hit.

Heavily populated areas are particularly impacted when severe winterstorms disrupt communication and power due to downed distribution lines. Snow and ice removal from roads and highways is difficult when accumulations build faster than equipment can clear. Debris associated with heavy icing may impact utility systems and transportation routes.

Damage to buildings occurs especially in areas where normally anticipated snowfall depths do not warrant recognition in building codes. Roof collapse damages residential, commercial, and industrial structures.
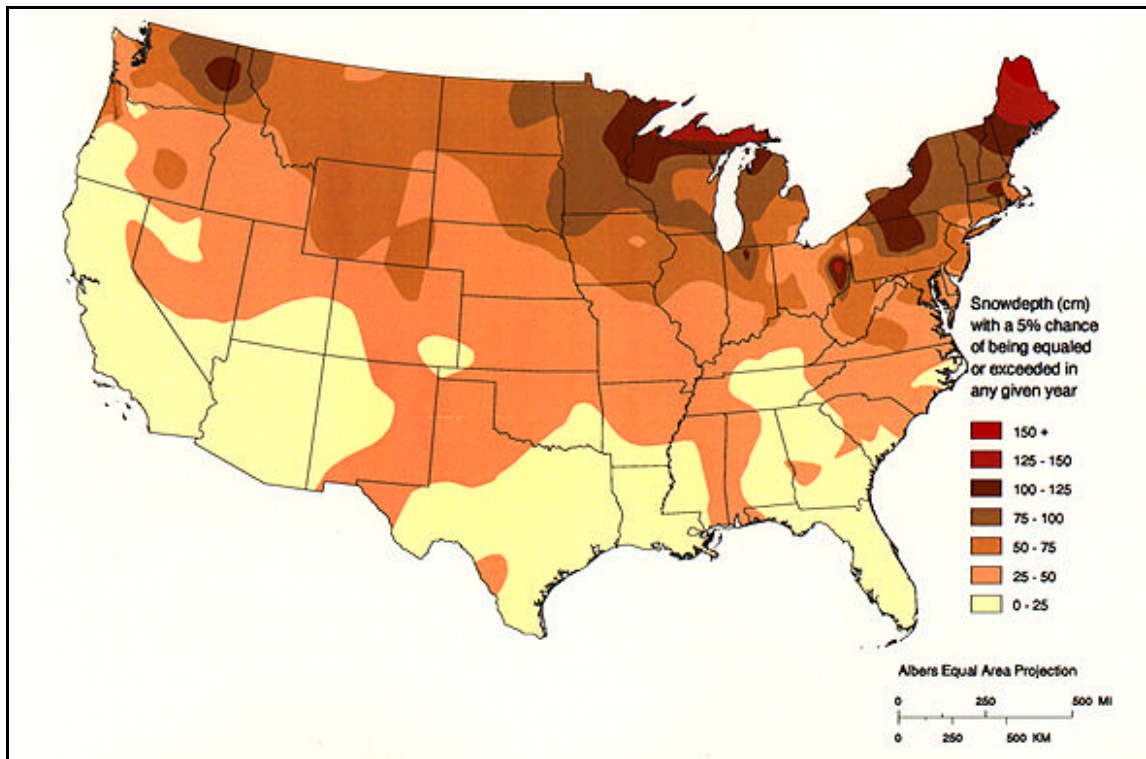
Map 7-1.   Snowdepth (in centimeters) with a 5% chance of being equaled or exceeded in any given year, from Solar and Meteorlogical Surface Observation Network 1961 - 1990
Data not shown for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Pacific Territories
(Source: Data from National Climatic Data Center, 1993)

The Superstorm of March 1993 illustrated that a severe winterstorm can be devastating. Table 7-1 presents the number of deaths and injuries and the estimated amount of damage resulting from the storm. In terms of reporting, NOAA found that problems arose in forecasting (before the event) and damage assessment (after the event). For example, NWS could have improved the coastal flood watches and warnings for the Florida Gulf Coast. An insufficient number of coastal observations and water-level measurements and a lack of storm-surge guidance products hampered effective forecasting.

Consequences

The occurrence of large snow storms, ice storms, and severe blizzards has a substantial impact on communities, utilities, and transportation systems, and often results in loss of life due to accidents or hypothermia. In addition to the impacts on transportation, power transmission, communications, agriculture, and people, severe winterstorms can cause extensive coastal flooding, erosion, and property loss.

Between 1988 and 1991, NWS recorded 372 deaths that could be attributed to snowfall, ice storms, or extreme cold weather, an average of 93 deaths per year. In 1991, winter snows and blizzards were responsible for the deaths of 37 people and injuries to 350 nationwide.

The Superstorm of March 1993 was among the worst non-tropical weather events in the United States, according to the Natural Disaster Survey Report published by NOAA (1994). The Superstorm caused more than $2 billion in property damage across portions of 20 States and the District of Columbia. It slowed commerce, snarled traffic, disrupted communications and power, and drove tens of millions of people indoors for extended periods of time during the worst of the storm.

The Superstorm is notable for its impact on a vast geographic area spanning virtually the entire eastern half of the United States. The NOAA report documents the impacts in six geographic regions, described below:

• The Florida Gulf Coast was struck by an unprecedented extra-tropical storm surge of 9 to 12 ft (3 to 4 m), damaging or destroying thousands of residences and businesses.

TABLE 7-1.—*Superstorm of March 1993: deaths, injuries, and damages by State*

State	Deaths Direct/ Indirect	Injuries	Estimated Damages (in millions)
Alabama	14/0	0	$100.0
Delaware	0/2	0	$0.5
District of Columbia	0/1	2	$0.5
Florida	28/22	150	$1,600.0
Georgia	15/0	420	$355.0
Maryland	1/0	0	$22.0
New York	8/0	4	$25.0
North Carolina	2/7	13	$13.5
Ohio	0/0	8	$5.0
Pennsylvania	4/48	0	$10.0
South Carolina	2/2	4	$22.2
Tennessee	2/13	0	$0.5
Virginia	0/11	0	$16.0
West Virginia	3/6	0	$0.5
Totals	**79/112**	**601**	**$2,170.7**

Information unavailable for Connecticut, New Jersey, Rhode Island, Massachusetts, Vermont, Maine, and New Hampshire

Source: *From NOAA, National Weather Service, 1994*

• Damage to the Southeastern States, particularly in southeastern Georgia and central eastern North Carolina, centered on beachfront property and marinas, although heavy inland agricultural damage caused by extremely high winds was reported. The storm caused considerable flooding along the Outer Banks of North Carolina.

• Areas of the southern Appalachians as far south as Alabama reported blizzard conditions, with heavy snow combining with rapidly falling temperatures and very high winds. Snow accumulation and frigid temperatures in northern Georgia collapsed roofs, downed power lines, and resulted in at least 27 fatalities, most of which were due to exposure.

• Blizzard conditions in the central Appalachians were less severe than those reported to the south, primarily due to reduced wind speeds. The worst snowfalls in five decades were reported in portions of eastern Kentucky and West Virginia. A state of emergency was declared in 25 counties in eastern Ohio due to snowfall and heavy winds.

• The Middle Atlantic and Northeastern States were hit hard by blizzard conditions. The greatest incidence of power outages was reported in the Washington, D.C., area. Outages resulted from the coupled effects of urban density and severe ice accumulation.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Snow, ice storm, and ice concentration data are collected at the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, MI. Data are analyzed and stored at the Snow and Ice Data Center at the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder.

Snow and ice research is conducted at the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, NH. Research addresses engineering and design for cold regions, cold weather hydrology, climatology of winterstorms, and studies on snow, ice, and permafrost.

The Snow Survey and Water Supply Forecasting Program operated by the Natural Resources Conservation Service in Portland, OR, determines the relationship of snowpack and potential runoff from mountain watersheds through field surveys. The network of data sites provides daily data on streamflow potential that are useful for predicting snowmelt runoff and preparing water supply forecasts.

MITIGATION APPROACHES

Experience has shown that no area can prepare fully for severe winterstorms. The Superstorm of March 1993 was among the most widely forecast winter events. Nonetheless, the unprecedented southward penetration of blizzard conditions paralyzed parts of the South for more than a week.

Specific snow and ice storm mitigation approaches and program information currently in use throughout the United States were not identified for review and incorporation into this report. However, measures may include enhanced building codes, planned deployment of resources, underground utility lines for critical facilities, and increased tree trimming along utilities.

RECOMMENDATIONS

Recommendations pertinent to severe winterstorm hazards are included in the 1993 *Natural Disaster Survey Report: Superstorm of March 1993* (NOAA, 1993).

BIBLIOGRAPHY AND REFERENCES

Byrant, E. 1991. ***Natural Disasters.*** New York, NY: Cambridge University Press.

Coch, N.K. 1995. ***GEOHAZARDS: Natural and Human.*** Upper Saddle River, NJ: Prentice Hall.

Kocin, P.J., and L. W. Uccellini. 1990. ***Snowstorms Along the Northeastern Coast of the United States: 1955 to 1985.*** American Meteorological Society, Meteorological Monographs. Vol. 22, No. 44.

National Climatic Data Center. 1993. ***Solar and Meteorological Surface Observation Network 1961–1990, Version 1.0. (CD-ROM).*** U.S. Department of Commerce, National Climatic Data Center, and U.S. Department of Energy, National Renewable Energy Laboratory.

NOAA, National Weather Service. 1994. ***Natural Disaster Survey Report: Superstorm of March 1993, March 12-14, 1993.***

EXTREME SUMMER WEATHER

Chapter Summary

Extreme summer weather is characterized by a combination of very high temperatures and exceptionally humid conditions. When persisting over a period of time, it is called a heat wave. Many areas of the United States are susceptible to heat waves.

The major threat of extreme summer weather is heatstroke, a medical emergency that can be fatal. Most at risk are outdoor laborers, the elderly, children, and people in poor physical health. The combined effects of high temperatures and high humidity are more intense in urban centers than in rural areas. The States that have experienced a higher degree of exposure to this hazard are Louisiana, Arkansas, Illinois, South Dakota, Arizona, Florida, and Pennsylvania.

Approximately 200 deaths a year are attributable to extreme heat. In 1980, when summer temperatures reached all-time levels in most of the Central and Southern States, more than 1,700 deaths were diagnosed as heat-related. A July 1995 heat wave caused 670 deaths—375 in the Chicago area alone.

Extreme summer weather is also hazardous to livestock and agricultural crops. It can cause water shortages, exacerbate fire hazards, and typically prompts excessive demands for energy. Roads, bridges, and railroad tracks are susceptible to damage from extreme heat. In the summer of 1988, a drought/heat wave in the Central and Eastern States resulted in $40 billion in damage as well as many fatalities.

Air conditioning effectively mitigates the effects of excessive heat on humans. However, a study by Kilbourne (1989) found that, at temperatures above 99°F, the increased air movement produced by fans may actually exacerbate heat stress.

HAZARD IDENTIFICATION

Generally, heat stress is divided into four categories (Table 8-1). Steadman (1979) developed a heat index that includes the combined effects of high temperature and humidity. The NWS gathers and compiles information used to estimate the index, and index values are distributed to the public and the weather broadcasting industry. The heat index is a measure of the severity of extreme summer weather.

An estimation of the heat index is a relationship between dry bulb temperatures (at different humidities) and the skin's resistance to heat and moisture transfer. Because skin resistance is directly related to skin temperature, a relation between ambient temperature and relative humidity versus skin (or apparent) temperature can be determined. If the relative humidity is higher (or lower) than the base value, then the apparent temperature is higher (or lower) than the ambient temperature.

Steadman (1979) presented data relating air temperature and relative humidity to the heat index or the apparent temperature using various factors. To indirectly arrive at a "heat index equation" using more conventional variables, a multiple regression analysis was performed on the data from Steadman's table.

The major human risks associated with extreme heat are described below.

- **Heatstroke.** Heatstroke, considered a medical emergency, is often fatal. It occurs when perspiration and the vasomotor, hemodynamic, and adaptive behavioral responses to heat stress are insufficient to pre-

vent a substantial rise in core body temperature. Although standardized diagnostic criteria do not exist, a medical condition is usually designated as heatstroke when rectal temperature rises above 105ºF as a result of environmental temperatures (Kilbourne, 1989). Patients may be delirious, stuporous, or comatose. Rapid cooling is essential to prevent permanent neurological damage or death. The death-to-care ratio in reported cases varies from 0 to about 40 percent, and averages about 15 percent (Vicario and others, 1986).

- **Heat Exhaustion.** Much less severe than heatstroke, heat exhaustion victims may complain of dizziness, weakness, or fatigue. Body temperature may be normal or slightly to moderately elevated. The primary cause of heat exhaustion is fluid and electrolyte (salt) imbalance due to increased perspiration in response to intense heat. Therefore, treatment is directed to the normalization of fluid and electrolyte status, and the prognosis is generally good (Knochell, 1974).

- **Heat Syncope.** Usually associated with exercise by people who are not acclimatized, heat syncope refers to a sudden loss of consciousness. Consciousness returns promptly when the person lies down. The cause is thought to be circulatory instability in response to heat, and the condition causes little or no harm to the individual.

- **Heat Cramps.** Heat cramps occur when people unaccustomed to heat exercise outdoors. The cramps are thought to be due to mild fluid and electrolyte imbalances and generally cease to be a problem after acclimatization (Knochell, 1974).
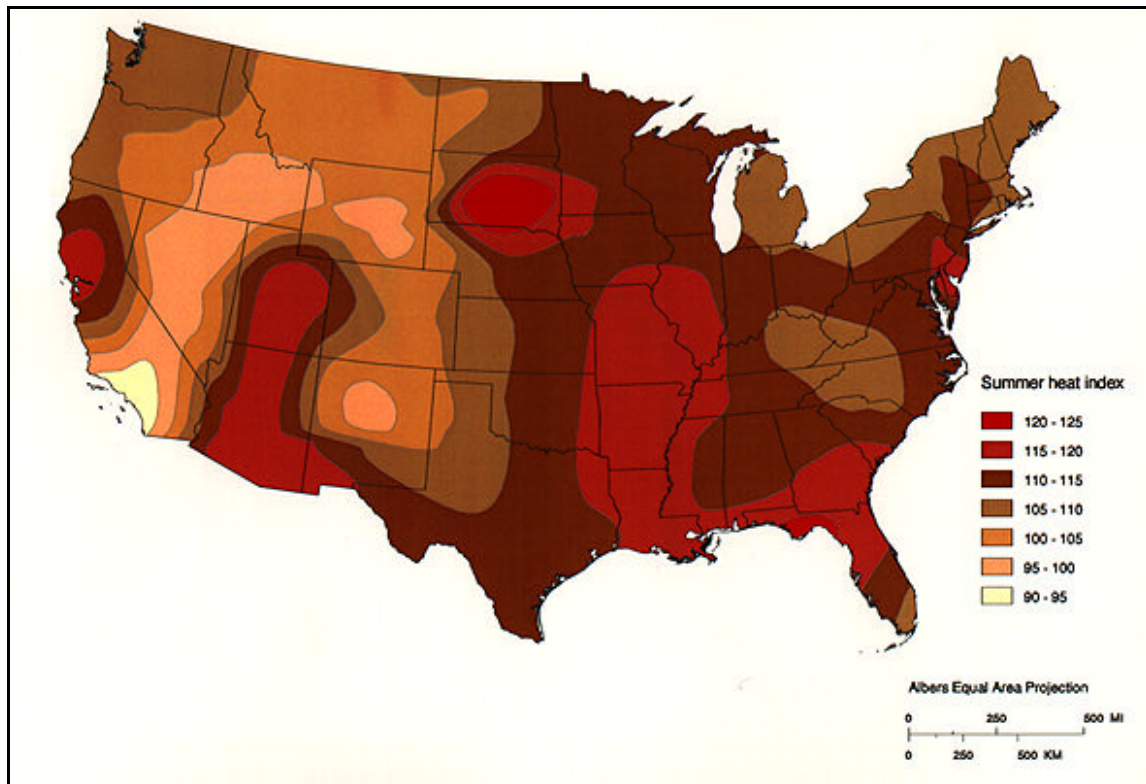
RISK ASSESSMENT

Probability and Frequency

The apparent temperature or heat index is a quantitative measure of extreme summer weather that can be used to characterize the probability and frequency of heat hazards. Map 8-1 shows one approach to describe the geographic distribution and frequency of extreme summer weather. It was developed from 30 years (1961-90) of relative humidity and temperature data at 48 climatic stations in the conterminous United States (NOAA and DOE, 1993).

TABLE 8-1.—*Heat index/heat disorders*

Danger Category	Heat Disorders	Apparent Temperature (^0F)
IV Extreme Danger	Heatstroke or sunstroke imminent.	>130
III Danger	Sunstroke, heat cramps, or heat exhaustion likely; heat stroke possible with prolonged exposure and physical activity.	105-130
II Extreme Caution	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and physical activity.	90-105
I Caution	Fatigue possible with prolonged exposure and physical activity.	80-90

Source: *From National Weather Service, 1997.*

Map 8-1.   Severity and areal extent of extreme summer heat in the United States, based on NWS heat
index. Data not available for Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands,
and Pacific Territories.
Source: *Data from U.S. Department of Commerce and Others, 1993.*

Because of the limited number of climatic stations, the map shows a broad generalization of trends in heat index, and may not show all areas that are subject to extreme summer weather.

Data used to compile Map 8-1 included hourly readings for between 2 p.m. and 5 p.m. for June, July, and August, assuming that the annual maximum temperature and relative humidity occurs during summer afternoons. The annual maximum values for the four time readings and the three months were used in a frequency analysis to determine the percent chance of a given heat index being exceeded in any year. The annual maximum values were ranked, and the annual percent chance of exceedance was computed by the Weibull plotting position formula to determine the heat index with a 5 percent chance of being exceeded in any given year. Minor adjustments to the data were required to address apparent measuring or recording errors, and temperatures below 70ºF were not used.

Exposure

Each year, many areas of the United States and its territories experience periods of prolonged high temperatures combined with high humidity. In susceptible areas, people usually are aware of the hazard, anticipate it, and are accustomed to avoiding its potentially dangerous effects. However, extreme summer heat does strike areas not accustomed to the phenomenon, where people tend to be less prepared.

The areas subject to heat index values in excess of 115ºF for the 5-percent-annual-chance event are the Southeastern, Southwestern, and Midwestern States (Map 8-1). Areas near the coast experience a combination of high temperatures and relative humidity that results in high apparent temperatures. Southwestern States experience low to moderate relative humidity, but extremely high temperatures.

Extreme summer weather poses the greatest danger to outdoor laborers, the elderly, children, people in poor physical health, and people residing in homes without air conditioning. During prolonged periods of extreme summer weather, local governments, voluntary organizations, and medical and health-care facilities may be burdened.

Previous research indicates that people over age 75 are most susceptible to extreme summer heat. The elderly are more likely to have chronic diseases or to be taking

medications that can increase risks. Sweating is the body's natural mechanism for reducing high body temperature, and the body temperature at which sweating begins increases with age. People taking neuroleptic and anticholinergic drugs should be counseled regarding possible increased sensitivity to heat (Kilbourne, 1989).

More deaths from extreme summer weather occur in urban centers than in rural areas. One reason that the effects of hot weather may be more extensive in urban areas is that poor air quality may exacerbate severe conditions. The masses of stone, brick, concrete, and asphalt that are typical of urban architecture absorb radiant heat energy from the sun during the day and radiate that heat during nights that would otherwise be cooler. Tall city buildings may effectively decrease wind velocity, thereby decreasing the contribution of moving air to evaporative and convective cooling. The heat differential was documented during the 1980 heat wave in Kansas City, where there was a difference of 2.5°C in the daily maximum temperature and 4.1°C in the daily minimum temperature between downtown and the suburban airport.

Consequences

In years during which a major heat wave does not occur in the United States, an average of approximately 200 heat-related deaths are reported (Kilbourne, 1989). When prolonged periods of abnormally high temperature or heat waves affect large areas, the number of deaths attributed to heat rises greatly. In 1980, when summer temperatures reached all-time highs in much of the Central and Southern States, over 1,700 deaths were identified as heat-related.

The Central Plains and Corn Belt States experienced a heat wave during July 15-19, 1995 during which apparent temperatures climbed above 120°F. A significant portion of the Eastern States was in the danger category during that same period, with apparent temperatures ranging from 105°F to 120°F.

The relative poverty of some urban areas may contribute to the severity of the extreme summer weather hazard. Low-income people are less able to afford cooling devices and the energy needed to operate them (Kilbourne, 1989).

The U.S. Department of Commerce reported that the 1995 heat wave caused 670 deaths—375 in the Chicago metropolitan area alone. Many deaths were among low-income elderly in residential units not equipped with air conditioning. Local utilities were forced to impose controlled power outages because of excessive energy demands, and water suppliers reported very low

levels of water in storage. This intense heat also caused the loss of tens of millions of cattle and poultry throughout the Midwest.

When heat waves are accompanied by drought, agricultural losses can be high. A drought/heat wave during the summer of 1993 affected the Southeastern United States, causing approximately $1 billion in damage and an undetermined number of deaths. Another drought/heat wave during the summer of 1988 affected the Central and Eastern United States, causing approximately $40 billion in damage and many deaths. A drought/heat wave during the summer of 1980 caused an estimated $20 billion in damage and many deaths.

Extreme summer weather can cause damage to roads, bridges, and railroads. High temperatures can be partially responsible for deflection of rails and related railroad accidents.

RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

Several scientists have attempted to develop mathematical models to quantify the increase in number of deaths expected for a given temperature increase. These models take into account such factors as the usual seasonal trends in mortality, acclimatization, the age of structures, and previous hot weather exposure of the at-risk population. However, they have not yet been useful in the prediction of adverse, heat-related health effects (Kilbourne, 1989).

MITIGATION APPROACHES

As with most natural hazards, public education about the effects of extreme heat and how to mitigate those effects is useful. NWS, through local television and radio announcements, alerts people about the onset of extreme summer weather and poor air quality. The alerts, advising high risk people to reduce physical activity and stay in air-conditioned buildings, have helped reduce fatalities and injuries.

BIBLIOGRAPHY AND REFERENCES

Kilbourne, E.D. 1989. "Heat Waves." In *The Public Health Consequences of Disasters 1989.* CDC Monograph. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, Atlanta, GA.

Knochel, J.P. 1974. "Environmental Heat Illness: An Eclectic Review." *Archives of Internal Medicine.* Vol. 133, pp. 841-864.

National Weather Serivice. 1997. Online. Accessible at http://www.nws.noaa.gov/sr/ohx/heat.htm.

Steadman, R.G. 1979. "The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science." *Journal of Applied Meteorology.* Vol. 18, pp. 861-873.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. July 1995. *Weekly Climate Bulletin.*

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. July 1995-September 1996. *Climate Outlook.*

National Oceanic and Atmospheric Administration, National Climatic Data Center, and U.S. Department of Energy, National Renewable Energy Laboratory. September 1993. *Solar and Meteorologic Surface Observation Network, 1961-1990, Version 1 on 3 CD-ROMs.*

Vicario, S.J., R. Okabajue, and T. Haltom. 1986. "Rapid Cooling in Classic Heatstroke: Effect on Mortality Rates." *American Journal of Emergency Medicine.* Vol. 4, pp. 394-398.